HETEROSIS AND COMBINING ABILITY FOR YIELD AND FIBER QUALITIES OF UPLAND COTTON UNDER HIGH DENSITY PLANTING CONDITIONS FOR INDIA

A Dissertation

by

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ABSTRACT

India is the leading producer of cotton in the world producing 33.8 million bales (170 kg each) from 11.5 million ha. However, the lower yields per unit area stimulated the concept of high density planting system in India. India grows *Gossypium hirsutum* (upland cotton) hybrids with Bt transgenic technology over 90% of the total hectareage. Current genotypes require a long growing season and the non-synchronous maturity demands multiple cycles of hand harvest. Breeding programs are working aggressively on product development suitable for high density planting. Identification of phenotypes that can be planted at higher densities, compact phenology, and improved agronomics will help India achieve an average yield of 766 kg ha^{-1}, which is the global average for upland cotton.

This study was conducted to compare level of heterosis and combining ability of compact and synchronous maturity US upland cotton cultivars when grown in US and India. Findings from this study should help Indian breeders to identify promising US cultivars for use in their breeding programs to transform the current robust, long duration genotypes to compact and synchronous maturity suitable for high density planting.

Of the thirty three diverse upland cotton cultivars from US used for line x tester study, significantly high best parent heterosis was observed in F_1 hybrids for yield (72.1% in US and 136.7% at India) and yield contributing traits. For fiber qualities medium to high heterosis was observed. Select US upland cotton cultivars were observed to be good general combiners for yield and quality traits. Tamcot 73 had good

GCA for seed cotton yield both at US (805 kg ha^{-1}) and India (259 kg ha^{-1}). For fiber length UA48 and TAM 94L-25 combined well at US and India while UA48 and Acala 1717-99 had significant GCA for fiber strength. To reduce the plant height TAM 73840 and TAM 0155 can be used since they had negative GCA both at India and US locations.

The line x tester results indicated preponderance of additive gene action over non additive for all the traits since variance due to line x tester interaction was less than variance to lines or testers.

The results suggest that careful selection of US cultivars and utilizing them to transform current Indian upland cotton genotypes suitable for high density planting is possible. Secondly, reasonably high heterosis observed for yield and other agronomic traits indicates that compact x compact F_1 hybrids can be bred without losing yield. Lastly pure line breeding scheme is recommended for improving fiber quality traits considering preponderance of additive gene action observed in this study.

DEDICATION

I dedicate this thesis to my late grandfather Baburao Saitwal who always inspired me for continuous learning. And to my wonderful family, friends and DuPont Pioneer who have provided me unconditional love and support during this journey.

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Contributors

This work was supervised by a thesis committee consisting of Professor Dr. C.W. Wayne Smith (Advisor) Dr. Steve Hague, Dr. Jane Dever, Dr. Hongbin Zhang Department of Soil and Crop Sciences and Dr. Tabare Abadie (Co-Advisor, DuPont Pioneer).

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NOMENCLATURE

lb	Pounds
Bt	Transgenic cotton
m ha	Million hectare
kg ha^{-1}	Kilogram per hectare
ha	hectare
CICR	Central Institute of Cotton Research, Nagpur, India
MTA	Material Transfer Agreement
NPBGR	National Bureau of Plant Genetic Resources, New Delhi, India
WGS	Whole Genome Sequencing
GCA	General Combining Ability
SCA	Specific Combining Ability
RFLP	Restriction Fragment Length Polymorphism
SSR	Simple Sequence Repeat
RAPD	Random Amplified Polymorphic DNA
ISSR	Inter Simple Sequence Repeat

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER I

INTRODUCTION

Cotton cultivation has been practiced for centuries and even today the cotton fiber is a major textile fiber. Cotton, a crop grown primarily for its fiber, is considered one of the major crops grown in over 50 countries worldwide (Smith, 1999). The world cotton production is estimated to be 102.55 million bales of 218 kg from 30.17 million hectors during 2016-17. India plants the most hectareage at 11.50 million ha and production of 27.5 million bales. For 2016-17, the cotton area in the United States (US) is 3.7 million ha and projected yield of 15.8 million bales. (USDA, 2016)

These statistics underline the importance of cotton for the US and India. While US farmers grow pure line cultivars, Indian farmers grow hybrid cultivars. Furthermore, agronomic practices, growing environments and pest disease scenarios differ vastly in both countries.

Indian cotton breeding focused on development of high yielding hybrid cultivars after the release of the world's first intra-*hirsutum* cotton hybrid H-4 in 1970. The release of the first Bt cotton hybrid in 2003 witnessed another landmark for cotton farmers, helping India to become the largest cotton grower and producer in the world. Even though India has the largest area (11.5 m ha) and it is the largest producer of lint (27.5 million bales), the average national productivity of India is one of the lowest in the world (i.e., 521 kg ha^{-1}). Australia (1905 kg ha^{-1}) ranks first in yield per unit land area followed by China (1614 kg ha^{-1}), Mexico (1565 kg ha^{-1}), Turkey (1537 kg ha^{-1}) and

Brazil (1506 kg ha^{-1}). Hence, there is an urgent need to increase the productivity of cotton in India to improve profitability for Indian growers and improve risk management. The scarcity of labor, stagnated yield levels, changing pest scenarios, and erratic rainfall patterns over the past few years are major challenges to the Indian cotton grower and are not under their direct control. One way to increase the yield level is through increasing plant density per ha.

All major cotton producing countries except India recommend plant populations ranging from 150,000 to 200,000 per ha. Currently, planting density in India, with row to row spacing ranging from 90 to 150 cm and plant to plant spacing ranging from 30 to 90 cm, allows 17,000-30,000 plants ha^{-1}. However, yields could be doubled by increasing plant density to 100,000 ha^{-1} comparable with other major cotton growing countries. It is important to breed for genotypes adaptable to the narrower spacing in order to increase yield per unit area instead of expecting hectareage under cotton to increase in the future. In fact, increasing per unit area productivity will free some area for other food crop cultivation.

Indian cotton breeding is going through a phase of rigorous changes to achieve the world average yield 766 kg ha^{-1}, by focusing on technology, production and post-harvest aspects. Major technology foci are biotechnology, plant architecture, fiber quality, and pest/disease tolerance. Increasing plant density will increase yield and improve input use efficiency and minimize land use to achieve food and fiber security (FICCI, 2012). While breeding for genotypes that are suitable for high density planting conditions, one question that needs to be answered is whether pure line cultivars will do better or will hybrids still offer higher yields? Understanding the extent of heterosis for a number of traits when crossing compact phenotypes under high planting density (over 98,800 plants ha^{-1}) in India and the US was a key focus of this study. Although the genotypes were exotic under Indian conditions, they represented cultivars bred for high density and machine picking which were compact and early to medium maturity from a number of germplasm pools within the US.

Current hybrids in India require a long growing season and the non-synchronous maturity of upland cotton requires multiple cycles of hand harvest. Breeding programs are working aggressively on product development for cultivars suitable for machine harvesting. Identification of phenotypes that can be planted at higher densities, with compact phenology, and with improved agronomics will help India achieve an average yield of 766 kg ha^{-1} which is the global average for upland cotton (Saitwal et al., 2014).

Exotic cotton cultivars were successfully used in India for developing hybrids and cultivars. The first intra-*hirsutum* hybrid H-4 and interspecific hybrid Varalaxmi had American Nectariless (exotic from US) and SB289E (a Russian *barbadense* cultivar) as parents. Many accessions within the US collection were identified as elite material by CICR, Nagpur for traits like early maturity, dwarf plant type, bacterial blight resistance, high boll number, high boll weight, high ginning percentage and high yield (Narayanan et al., 2014). However, US cultivars are generally susceptible to sucking pests which makes them unadaptable to India’s environment and thus breeders have not used them extensively in line development programs. Public and private breeding programs in India are aggressively working to develop genotypes suitable for high density conditions. US cultivars could be successfully used to breed for synchronous maturity and better fiber quality without compromising yield provided suitable germplasm sources were identified as donor parents. Since this involves germplasm sharing, proper procedures like MTA and germplasm import procedures as per guidelines from NPBGR, New Delhi must be strictly adhered.

Heterosis has been studied by plant breeders all over the world, and the theory of heterosis is being continually improved (Zhang et al., 2010). Heterosis is the superiority of the hybrid over the mid parent, better parent, or a standard check. Heterosis results from allelic or non-allelic interactions of genes under the influence of a particular environment (Ranganatha et al., 2013). To develop potential hybrids in cotton, it is necessary to exploit genetic diversity available in the form of visible differences in plant morphological traits as well as allelic differences at loci contributing to the trait under consideration. One possible way is the use of the F_1 hybrid between robust and compact parental types which can lead to an improvement in productivity as a result of superimposition of the desirable features of these contrasting plant types (Anuradha, 1998). However, there is no genetic theory available to precisely select parents for hybridization which will result in superior hybrid combination. Estimating combining ability effects is a method of choice for breeders to screen and select parents for heterosis breeding (Sandhu and Chahal, 1995).

With the advent of modern high through put DNA sequencing methods, development of computer software programs to analyze large molecular data sets and plummeting cost for genotyping, Whole Genome Prediction (WGP) has become method of choice and genomic prediction models are being developed to predict performance of inbred lines and potential hybrids before they go to actual field testing (phenotyping). Many studies have indicated strong potential for genomic prediction in maize and other crop species (Wallace et al., 2014).

Since heterosis is associated with the interaction of different alleles at a locus (Jones, 1945; Anand et al., 2012), it has been suggested that molecular marker diversity may be used to select parents for hybridization. In diploid rice, genetic distance based on molecular marker diversity did not predict heterosis for all traits; however, it showed significant correlation with grain yield and other traits in autotetraploid rice (Wu et al., 2013). In cotton, many efforts have been made to investigate the relationship between DNA marker based genotypic variation of the parents to be used in a hybrid breeding program and heterosis with varying results (Meredith and Brown, 1998; Wu et al., 2002; Zhang et al., 2007; Alkuddsi et al., 2013).

The present study was undertaken with following objectives;

1. To compare performance of select US upland cotton cultivars and understand the level of heterosis in F_1 hybrids through the use of a line x tester design when grown in the US and in India.
2. To estimate and compare combining ability effects of select US cultivars when grown in US and India

CHAPTER II

LITERATURE REVIEW

Heterosis, GCA and SCA estimates using line x tester analysis

The line x tester (L x T) design is basically an extension of a top cross analysis in the sense that instead of one tester, as used in topcrossing, more than one tester is employed in the L x T design (Kempthorne, 1957). These testers provide a common genetic background, jointly as well as individually, against which lines/genotypes are tested. General combining ability (GCA) for lines and testers and specific combining ability (SCA) for each cross can be determined (Singh and Chaudhary, 1977).

Shull (1914) first coined the term heterosis which was the opposite of inbreeding depression. Heterosis is defined as an increase in vigor or production of economic product of the F_1 generation over the mean of the parents or over the better parent (Hayes et al., 1955). The phenomenon of heterosis has been known in cotton since 1894, when Mell (1894) first reported increase in agronomic and quality traits in cotton hybrids; followed by Balls (1908) who reported heterosis in interspecific cotton hybrids. Since then, many studies have been conducted to estimate heterosis, GCA and SCA effects and gene action for yield, yield contributing traits and fiber qualities in cultivated cotton from across major cotton growing countries.

In cotton, heterosis and recombination breeding has been successful. The first successful hybrid H-4 released in India exhibited 170% heterosis for seed cotton yield over its female parent G-67 across three years of large scale trials during 1966-69 (Basu and Paroda, 1995). Higher yields, wider adaptability, seed production network, skilled labor availability and better price spurred the development of many superior hybrids by both public and private sectors in India. Heterosis for yield in F_1 hybrids developed for production in India from 1947 to 1972 ranged from 7% to 50% for interspecific hybrids and from 10% to 138% in intraspecific hybrids (Davis, 1978). Singh et al. (2003) reported useful heterosis for the past ten years from 1807 crosses for three traits, namely halo length (27.5 to 31.5%), ginning percentage (4.3 to 16.9%) and lint index (28.9 to 58.3%). F_1 lint yield ranged from 92% to 115% of that of Deltapine 16, while F_2 yields ranged from 86% to 107% (Meredith and Bridge, 1972). Wu et al. (2010) reported heterosis in cotton F_2 hybrids ranging from -30% to 76% over the best parent for seed cotton yield. Others (Hassan et al., 1999; Khan et al., 2009; Alkuddsi et al., 2013) reported similar positive and negative heterotic values, demonstrating the potential of hybrids in upland cotton. Higher heterosis in F_1 hybrids is also associated with higher inbreeding depression; therefore, moderate type of heterosis has some stability in segregating populations (Tang et al., 1993; Soomro, 2000; Soomro and Kalhoro, 2000). However, Panni et al. (2012) compared F_2 populations with respective F_1s and concluded that 62% of F_2 populations exhibited negative values for inbreeding depression. Similar results were shown by Karademir et al. (2011) while evaluating cotton F_1 and F_2 hybrids under drought stress situations emphasizing the value of F_2 hybrids.

The concept of combining ability was introduced by Sprague and Tautum (1942). They recognized two types of combining ability, i.e., general combining ability

(GCA) and specific combining ability (SCA). GCA is the average performance of a line or genotype in a series of cross combinations while SCA is the performance of specific cross/hybrid combination. GCA is associated with genes additive in their effect while SCA is attributed primarily to deviations from additive effects and due to dominance and epistasis. In practical breeding, GCA helps to identify an individual parent or genotype having a significant impact on the trait under consideration when crossed with all other parents in the study while SCA effects identify the best hybrid combinations and complementary alleles (Kearsey and Pooni, 1996; Ragsdale et al., 2003) for trait performance which can be used in transgressive breeding.

Previous studies showed that variation in seed cotton yield and fiber quality traits were influenced by additive and non-additive gene action. Myers and Lu (1998) reported that GCA effects were more significant than SCA effects for micronaire, upper-half mean length, fiber strength, and elongation, suggesting that additive gene action is important for these traits. Bhardwaj and Kapoor (1998) revealed that seed cotton yield and lint index were controlled by additive genetic variance and non-additive genetic variance, on the other hand ginning percentage was controlled by additive genetic variances. Green and Culp (1990) found that GCA effects were significant for all fiber properties except uniformity index. Cheatham et al. (2003) reported that fineness and length exhibited primarily dominance genes effects; fiber percentage and fiber strength were controlled by additive genes effects; and fiber yield and fiber elongation were controlled equally by additive and dominant genes. Roysdale (2003) reported additive gene action for ovules and seed number per boll within the set of parents used in his study. Samreen et al. (2008) found that GCA effects were higher than SCA effects for seed cotton yield, boll weight, boll number per plant, and ginning out turn indicating effect of additive gene action for expression of these traits. Karademir et al. (2009) concluded that both additive and non-additive gene effects were significant. Seed cotton yield, fiber strength, ginning percentage and fiber uniformity were influenced by non-additive gene action while fiber length, fiber fineness and fiber elongation by additive gene action. Wajid et al. (2011) reported additive gene action for sympodial branches, bolls per plant, seed cotton yield and lint percentage. Sawarkar et al. (2015) reported predominance of non-additive gene action for all 14 traits under study except plant height, 2.5% span length and oil content.

Parental diversity, genetic distance and its correlation with F_1 hybrid performance

Knowledge of the nature and magnitude of genotypic and phenotypic variability present in any crop species plays a vital role in formulating a successful breeding program for producing superior cultivars. Genetic diversity is essential for breeders to explore traits of interest and introgress them as needed. This role of genetic diversity in crop vulnerability is widely acknowledged. According to quantitative genetics theory, the probability of producing unique genotypes increases proportionally with the number of genes in which both parents differ. However, many empirical evidences of using related parents to breed high yielding cultivars has put a question mark on this theory (Esbroeck and Bowman, 1998).

Many studies have been conducted anticipating the role of genetic diversity and genetic distance within lines to identify suitable parents. Esbroeck and Bowman, (1998) analyzed coefficients of parentage in cotton cultivars and concluded that it was not imperative for improvement in cotton and most successful cultivars were developed from closely related parents. Sandhu and Chahal, (1995) attempted to develop a numerical relationship of yield of F_1 hybrids with the characters of the parents in upland cotton. They concluded that the final yield potential of an F_1 hybrid is a complex interaction and that there is in general no relationship between observable characters and the F_1 yield. However, Darvishzadeh (2012) suggested a significant relationship among morphological distance and F_1 performance, SCA and heterosis in Sunflower. Botao (2016) while working on chromosome substitution lines in cotton concluded that the relationship between heterosis and genetic distance for yield traits is complicated and requires further study. In general, there is poor relationship between parental morphological diversity and F_1 performance in cotton and other crops.

The use of line *per se* molecular data has been suggested as a means of predicting hybrid performance. Considerable research is being conducted in all major field crops, including cotton. Meredith and Brown (1998) studied the relationship between genetic distance and F_2 hybrids performance by using RFLP markers in a study comprising 15 cultivars, one strain and 120 F_2 hybrids and concluded that the correlation were very low (r=0.08). Gutiérrez et al. (2002) genotyped five US and four Australian cultivars and two-day neutral converted lines of upland cotton with SSR markers to study diversity and its relation with F_2 population performance. They concluded that genetic distance was a poor predictor of overall F_2 performance. Similar results were reported by Wu et al. (2002) when RAPD, ISSR, SSR markers were employed to calculate genetic distance of six domestic and two exotic cultivars. Zhang et al. (2007) studied the relationship between parental molecular marker diversity and hybrid performance in both intra and inter specific hybrids of cotton to evaluate the feasibility of predicting hybrid performance using molecular markers. Genetic distances (GD) among the parents were calculated from 56 RAPD and 66 SSR marker data, and their correlation with hybrid performance and heterosis determined. The conclusion was that the power of predicting hybrid performance using molecular markers in cotton is low.

Alkuddsi et al. (2013) developed 110 F_1 interspecific hybrids in cotton and calculated the genetic distance among parents using 40 SSR markers. They detected a low but significant correlation of genetic distance with hybrid performance and heterosis.

CHAPTER III

LINE X TESTER ANALYSIS FOR YIELD, AGRONOMIC AND FIBER QUALITY TRAITS

Plant materials

A total of 35 upland cotton genotypes representing various breeding programs and areas of adoption were selected for this study. Seeds for these genotypes were obtained from the Cotton Improvement Lab, Texas A&M AgriLife Research and Dr. James Frelichowski, Curator, U.S. National Cotton Germplasm Collection, Southern Plains Agricultural Research Center, Crop Germplasm Unit, at College Station, Texas. Pedigrees and registration year for these 35 cotton genotypes are summarized in Table 1.

Thirty three of these 35 genotypes were imported to India through the National Bureau of Plant Genetic Resources (NBPGR), Indian Council of Agricultural Research, New Delhi; per import permit No. 236/2014, dated 3 May 2014. Two breeding lines viz., TAM 13P-54ELS and TAM 06WE-621 which are proprietary germplasm to Texas A&M University were not imported.

Table 1. Details on parental genotypes representing various upland cotton cultivars from US breeding programs for heterosis and combining ability studies using line x tester design.

Genotype	Year of Registration*	Developed from	PI No**	Pedigree	Remarks
TAM 94L-25	1993	Texas	PI 631440	TAM 87G3-27//Stoneville 213/(Lankart 57/Deltapine 14/Rogers Acala/Gregg/Fox/)	Breeding line, early maturity, high length and strength
PSC355	1999	Mississippi	PI 612974	DES 949/Acala 1517-88	Owned by Phytogen Seed Company, LLC.
Tamcot Sphinx	1995	Texas	PI 592801	[(Tamcot CD3Hx Para Inta) x Paymaster 145].	Boll storm resistant, hirsute, good resistance to insect and pest
Acala 1517-99	1999	New Mexico	PI 612326	B742/E1141	Excellent fiber length, resistance to wilt, bacterial blight. High lint percentage (>40%)
Acala Maxxa	1990	California	PI 540885	T7538/S4959	
Tamcot 73	2011	Texas	PI 662044	93WB-57s x 95WE-48	Better yields, fiber length and uniformity
TAM 88G-104	2001	Texas	PI 614941	DP90/CS-8606	High Yield, excellent fiber, resistance to whiteflies
TAM 86 GGG-30	1994	Texas	PI 578056	PD6520/Acala 1517-70//1656-71-2c-1-1/Delcot 277	Short fruiting branch, high fiber strength, susceptible to major insect pest and diseases
TAM 0155	1990	Texas	PI 540255	Multi parent cross	Compact, early, storm resistant
TAM 73840	1990	Texas	PI 540259	Multi parent cross	Compact, determinate, large bolls, storm resistant
CS8601	1988	Texas	PI 607272	Multi parent cross	Early maturity
CS8606	1988	Texas	PI 513288	Multi parent cross	Early maturity
All Tex 7A21	NA	Texas	NA	NA	Developed by All-Tex Seed, INC, Texas
UA48	2012	Arkansas	PI 660508	Arkot 8712 / FM 966	Early maturity, high competitive yields, exceptional fiber quality
LA 887	1991	Louisiana	PI 547084	LA 434-RKR/DES 11-9	High Yield, premium fiber.
MD 51ne	1993	Mississippi	PI 566941	BC2F2 selection from MD65-11ne/ DP90	Nectariless, good yields, fiber strength

Table 1. Continued.

Genotype	Year of Registration*	Developed from	PI No**	Pedigree	Remarks
Stoneville 213	1962	Mississippi	PI 529229	Sel. Of Stoneville 7	Mississippi obsolete variety
Des 422	1982	Mississippi	PI 529519	Deltapine 55/DES 2134-018	Mississippi obsolete variety
Delcot 277	1972	Mississippi	PI 529258	Rex//TJ/EF 310	Mississippi obsolete variety
Deltatype Webber	1936	Mississippi	PI 528717	Sel. Of Webber 82	Mississippi obsolete variety
Lightning Express	1936	Mississippi	PI 528978	Sel. Of Express 350	Mississippi obsolete variety
Lone Star	1936	Mississippi	PI 528636	Sel. Of Jackson Round Boll	Mississippi obsolete variety
Mebane	1936	Mississippi	PI 528985	Sel. of Boykin	Mississippi obsolete variety
Rex	1989	Arkansas	PI 529140	BBR/2*Empire	Mississippi obsolete variety
DP16	1989	Mississippi	PI 529251	DP Smoothleaf/Fox 4-4205	Mississippi obsolete variety
DP50	1984	Mississippi	PI 529566	DP16//DP Smoothleaf/DP 45/3/DES 56	Mississippi obsolete variety
DP90	1984	Mississippi	PI 529529	DP 6516/DP6582	Mississippi obsolete variety
GA 161	2001	Georgia	PI 612959	81-29/Coker315//79-13/DP90/3/Aub-244RNR/4/M-725RNR/5/PD6208	Yield and fiber quality
Auburn 56	1989	Alabama	PI 529215	Cook 307-2/CKR100//CKR100W	Mississippi obsolete variety
SC1	1979	South Carolina	PI 529598	CKR 421/PD4398	Mississippi obsolete variety
PD6520	1979	South Carolina	PI 529624	NA	Mississippi obsolete variety
Ciano Alamos 92	1994	Mexico	PI 570665	Deltapine 80/TAMU 1209	
Ciano Cocorim 92	1994	Mexico	PI 570666	Stripper 61-28/Ca 1012	Cluster type
TAM 06WE-621	2014	Texas	PI 671964	DP 491/TAM96WD-18//TAM91C-95Ls/DP Acala 90	Fiber bundle strength
TAM 13P-54	NA	Texas	NA	TAM B182-33 ELS/TAM00S-36/TAMB182-31	UHML

* Year of registration with Registered with the Crop Science Society of America, 677 South Segue Rd., Madison, Wisconsin 537 11.
** GRIN ID as per US National Plant Germplasm System (NPGS)

Crossing block for F_1 hybrid seed production

The 35 genotypes were planted at the Texas A&M AgriLife Research Farm, College Station, TX during 2014. Five genotypes (TAM94L-25, PSC355, Tamcot Sphinx, TAM 13P-54 ELSU and TAM06WE-621) were planted as tester rows and treated as females, while the remaining 30 genotypes (Table 1) were planted as line rows and treated as males.

In India, the imported 33 lines, excluding TAM 13P-54 ELSU and TAM 06 WE-621 testers were planted on 16 September 2014, at a green house facility of Pioneer Overseas Corporation, Hyderabad, India. After post quarantine clearance from the Inspection Scientist, NPBGR, crossings were initiated on 13 November 2014.

Female rows were hand emasculated, stigmas were covered by a straw tube and pollinations were executed the following day in a line x tester fashion to generate 150 F_1 combinations at College Station, Texas and 90 F_1 combinations at Hyderabad, India. Each cross was assigned a unique number for identification purposes.

Simultaneously, selfing of all 35 parental lines was effected to produce selfed seed required for field testing. At harvest, crosses were harvested separately while self-seeds were bulked within individual genotypes.

Selfed parental and F_1 seeds were used in 2015 at two locations (College Station and Weslaco) in Texas USA and two locations (Aurangabad and Hyderabad) of the Pioneer Overseas Corporation research farms, India.

Field evaluations

India locations

Field performance testing was carried out at two locations in India, Aurangabad, Maharashtra State and Hyderabad, Telangana State, at the Cotton Research Centers, Pioneer Overseas Corporation-India Branch, India. The soil types were black cotton soils, clay loam and medium black sandy loam, respectively. At both locations, a total of 126 entries, including 90 F_1 hybrids (developed with TAM94L-25, PSC355, and Tamcot Sphinx as testers), all parents (30 lines and 3 testers) and three standard cultivar checks totaling to 126 entries were planted in a randomized complete block design with three replications. Aurangabad location was planted on 22nd June 2015 while Hyderabad on 25th June 2015 representing normal planting window of the states. Plots were two rows x 3m x 0.6 m (Aurangabad) or 0.7 m (Hyderabad), with 21 plants per row. These experimental plots thus contained approximately 98,800 plants per ha, which is within the lower portion of plant populations for production of upland cotton in the USA. Recall that India currently grows hybrid cotton at an average plant density of only 23,500 plants per ha.

All plots were managed using standard cultural practices for cotton production in India, including drip irrigation, fertilization and need-based pest control measures, especially for the sucking pest and boll worm complex. At maturity, 30 bolls per entry per replication were hand-harvested from the first and second fruiting positions in the middle of the fruiting zone. Samples were ginned on a mini roller gin without lint cleaner. Fiber samples were analyzed using high volume instrument (HVI) at the Fiber testing lab, CIRCOT, Guntur (AP) India. The reader should note that uniformity of fiber length qualities were expressed differently at Lubbock, US and Guntur, India although both labs used HVI.

Table 2. Morphological traits recorded at Aurangabad (AWB) and Hyderabad (HYD), India.

Trait	**Abbreviation**	**Description**	**AWB**	**HYD**
Seed cotton yield (kg ha^{-1})	YLD	Calculated from total weight of seed cotton harvested from net plot	Yes	Yes
Plant height (cm)	PLTHT	Average plant height of randomly selected 3 plants per plot	Yes	Yes
Boll weight (g)	BOLWT	Average seed cotton weight per boll from 30 randomly hand-picked bolls.	Yes	Yes
Gin out turn (%)	GINOT	Amount of lint in a random sample of hand harvested seed cotton expressed as a percent of seed cotton in the sample.	Yes	Yes
Number of ovules	OVCNT	Average of number of ovule per boll from random 3 bolls	Yes	Yes
Number of seeds	SDCNT	Average of number of seeds per boll from random 3 bolls	Yes	Yes
Seed Index	SDINX	Weight in grams for 100 seeds selected randomly.	Yes	Yes
Fiber length (mm)	SL	Fiber length reported in millimeters, expressed as 2.5% Span Length.	Yes	Yes
Fiber strength (kN m kg^{-1})	STR	Expressed as kilonewton meter per kilogram	Yes	Yes
Micronaire	MIC	Micronaire is a measure of the maturity and/or the fineness of cotton fibers and is reported in micronaire units.	Yes	Yes
Fiber uniformity (ratio)	UR	Fiber uniformity ratio is a relative measure of the length uniformity of cotton fibers. Calculated as UR= (50% span length / 2.5% span length) x 100	Yes	Yes
Fiber elongation	ELONG	Elongation is the degree of extension of the fibers before break occurs when measuring strength.	Yes	Yes

US locations

Field performance testing was carried out at two locations, i.e., College Station and Weslaco at the Texas A&M AgriLife Research Farms. The soil types were Westwood sandy loam, a fine-silty, mixed thermic Fluventic Ustochrept, intergraded with Ships clay, a very fine, mixed, thermic udic chromustert at College Station and Hildago sandy clay loam, a fine-loamy, mixed, active, hyperthermic Typic Calciustoll, at Weslaco. At Weslaco, a total of 166 entries including 150 F_1 hybrids, five testers and three commercial checks (Tamcot 73, TAM 13Q-18, DP491) were planted on 13th March 2015, in a randomized complete block design with three replications of single row plots, of 6 m x 1 m, with 15 plants per row. Ten plants of each plot were harvested for yield data. All cultural practices, including furrow irrigation, were normal for the Lower Rio Grande Valley of Texas.

College Station field experiment was comprised of 90 F_1 hybrids, three testers (TAM94L-25, PSC355, Tamcot Sphinx), 30 lines, and three commercial checks and two elite fiber quality strains from the Texas A&M AgriLife Research cotton breeding program, TAM 13P-54 ELSU (extra-long staple upland) and TAM06WE-621 (extra strength upland) thus totaling 128 entries planted in two replications on 28th April 2015. Plot size was the same as Weslaco and all cultural practices, including furrow irrigation, were normal for central Texas cotton production. At harvest, 30 bolls per entry per replication at each location were hand-harvested from the first and second fruiting positions in the middle of the fruiting zone. Samples were ginned on a laboratory saw gin without lint cleaner. Fiber samples were analyzed using HVI fiber properties at the

Fiber and Biopolymer Research Institute (FBRI) in Lubbock, Texas. Data collected at the US sites are summarized in Table 3.

Table 3. Morphological traits recorded at Weslaco (WS) and College Station (CS), US.

Trait	**Abbreviation**	**Description**	**WS**	**CS**
Seed cotton yield (kg ha^{-1})	YLD	Calculated from total weight of seed cotton harvested from net plot	Yes	No
Plant height (cm)	PLTHT	Average plant height of randomly selected 3 plants per plot	Yes	No
Gin out turn (%)	GINOT	Amount of lint in a random sample of hand harvested seed cotton expressed as a percent of seed cotton in the sample.	Yes	Yes
Number of ovules	SDCNT	Average of number of seeds per boll from sample of random 10 bolls	No	Yes
Number of seeds	OVCNT	Average of number of ovules per boll from sample of random 10 bolls	No	Yes
Fiber Length (mm)	UHM	Fiber length is reported in hundredths of an inch as measured by HVI expressed as upper half mean.	Yes	Yes
Fiber Strength (kN m kg^{-1})	STR	Expressed as kilonewton meter per kilogram	Yes	Yes
Micronaire	MIC	Micronaire, is a measure of the maturity and/or the fineness of cotton fibers, reported in micronaire units.	Yes	Yes
Fiber Uniformity (index)	UI	Fiber uniformity index (UI) provides a relative measure of the length uniformity of cotton fibers. Uniformity Index is calculated as UI= (mean length / upper half mean length) x 100	Yes	Yes
Fiber Elongation	ELONG	Elongation is the degree of extension of the fibers before break occurs when measuring strength.	Yes	Yes

Statistical analysis

Before proceeding with the analysis of variance (ANOVA), normality was checked by Shapiro-Wilk test (W statistic) using the proc univariate method while homogeneity of variances (HOV) was checked using Levene's HOV test using SAS Version 9.4 (SAS institute, 2013) for individual locations as well as combined location analysis. In India, all of the traits showed significance indicating non normality of the data except fiber length for which data were normally distributed at individual and combined locations; yield and ginning out turn at Aurangabad location and boll weight which was normally distributed at Hyderabad location. Variances were homogeneous for fiber strength at Aurangabad while plant height, seed index and micronaire variances were homogeneous at Hyderabad location. Only uniformity variances were homogeneous when locations were combined.

At the US locations, similar results were obtained for normality and homogeneity of variances. At Weslaco, gin out turn and fiber uniformity was normal while at College station only fiber strength was normal. All traits showed heterogeneous variances for individual locations, however, when locations were combined, variances for gin out turn, fiber length, fiber strength and uniformity were homogeneous.

Distribution analysis from JMP Pro 12 (SAS Institute, 2013) revealed skewness of data with outliers at both India and US locations. It is interesting to note that for plant height, bimodal or double peaked distribution was observed at India locations. This may be due to inclusion of diverse parents, hybrids and standard checks in experiments and non-adapted US cotton genotypes (exotic) under Indian growing conditions. Data transformation did not help to overcome the heterogeneity of error variances. Since the main aim was to estimate heterosis, GCA and SCA effects, ANOVA was performed considering as if the variances were homogeneous.

The Proc GLM (General Linear Model) procedure of SAS was used to perform an ANOVA for all traits at each location and with locations combined. Combined analysis was performed separately for the India and US locations where genotypes and locations were considered fixed effects and replications were random.

Location-wise line x tester analysis of variance was performed for all traits including only hybrids and parents (checks not included) using R software and package 'agricolae' (R core team, 2016; Mendiburu, 2009, Sigh and Chaudhary, 1977). For combined line x tester analysis, the Proc GLM procedure of SAS was used and variances were calculated as described by Sharma (1988). For US locations, only hybrids were included in the analysis. The GCA and SCA effects were calculated and significance tested by calculating standard errors as described by Sharma (1988).

The additive model used to estimate GCA and SCA effects was,

$$y_{ijk} = \mu + g_i + g_j + s_{ij} + e_{ijk}$$

where;

y_{ijk}= yth observation in kth replication involving cross of i and j, μ = population mean, g_i=GCA effect of ith female parent, g_j=GCA effect of jth male parent, s_{ij}=SCA effect of ijth combination, e_{ijk} = error associated with the observation y_{ijk} , i=1,….,f (f= Number of females), j=1,…,m (m=Number of males), k=1,…,r (r = Number of replications).

The individual effects are estimated as follows;

Overall mean= $\hat{\mu} = \frac{X...}{mfr}$

where $X_{...}$ =total of all hybrid combinations over all replications.

GCA effect of each line = $\widehat{g_\iota} = \frac{Xi..}{mr} - \frac{X...}{mfr}$,

where $X_{i..}$, is total of the i[th] female over all male parents and replications.

GCA effect of each tester= $\widehat{g_J} = \frac{X.j.}{fr} - \frac{X...}{mfr}$,

where $X_{.j.}$is total of the j[th] male over all female parents and replications.

SCA effects of hybrids= $\widehat{s_{\iota J}} = \frac{Xij.}{r} - \widehat{g_\iota} - \widehat{g_J} - \hat{\mu}$

where $X_{ij.}$ is total of the X_{ij}[th] hybrid combination.

The standard errors for combining ability effects were calculated as below,

Standard Error (S.E.) for GCA effect, lines =S.E. $g_i = \sqrt{\frac{(f-1)\ EMS}{mfr}}$

Standard Error (S.E.) for GCA effect, tester =S.E. $g_j = \sqrt{\frac{(m-1)\ EMS}{mfr}}$

Standard Error (S.E.) for SCA effect =S.E. $s_{ij} = \sqrt{\frac{(f-1)(m-1)\ EMS}{mfr}}$

where EMS is error mean square from ANOVA (Sharma, 1988)

The 't' values were then calculated to test significance of the combining ability effects by dividing the combining ability effect with its respective standard error value and comparing that value with the corresponding tabular t value at the appropriate error degrees of freedom.

Magnitude of heterosis in terms of percent increase or decrease of F_1 hybrids over the best parent (heterobeltiosis) was calculated as:

$$\text{Heterosis}=\left(\frac{F_1-\overline{BP}}{\overline{BP}}\text{ X }100\right)$$

Here $\overline{BP}$ denotes the average performance of best parent.

Standard errors for testing significance of heterosis for the combined analysis at the India locations were calculated as suggested by Soehendi and Srinives (2005) since heterogeneity of variances was observed. Location-wise significance of heterosis from the US locations was tested as suggested by Singh et al. (2004) since most of the traits had homogeneous variances.

Results and Discussion

India locations

Parental evaluations

Prior to line x tester analysis and in order to include three Indian cultivars for comparison purposes, an ANOVA was performed across locations to test the significance of differences among genotypes, including hybrids and parents, as well as to understand their performance compared with the standard check genotypes. Analysis indicated significant differences among the entries tested for all traits (Table 4). The Genotype x Location interaction was significant for all traits except GINOT, SDINX, STR, MIC and UR, suggesting that entries did not respond equally to these Indian locations.

Table 4. Mean squares from combined analysis of variance for indicated traits in upland cotton at Aurangabad and Hyderabad, India 2015.

S.O.V.	df	OVCNT †	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
Loc	1	1032.9*	1087.9*	45294952**	211.2**	739406.6**	2.1	1.4	40.5	4486.8	5.1	2.6	20.46
Rep (loc)	4	55.4	10.6	272613	6.1	137.3	6.83	15.6	23.1	48073.7	7.8	89.3	2.52
Genotype (Gen)	125	6.3**	9.0*	387170**	1.3**	206.8**	17.8**	4.12**	9.17**	1151.3**	0.31**	3.8**	0.09**
Gen*Loc	125	4.5**	7.2*	209202**	0.6**	107.6**	0.25	0.07	2.0**	177.1	0.04	1.2	0.05*
Error	500	2.8	4.2	54687	0.2	66.6	1.9	1.06	1.2	469.4	0.08	0.9	0.03
C.V. (%)		5.2	6.7	23.7	12.4	9.0	3.5	10.9	3.7	10.1	10.2	2.0	3.4

*Significant at P=0.05
** Significant at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g); SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

For discussion purposes, a separate analysis of variance was conducted for parental genotypes (lines and testers) and Indian standard checks, i.e., excluding hybrids (Table 5). Location effects were significant for the following agronomic traits: OVCNT, SDCNT, YLD, BOLWT, and PLTHT while non-significant for all fiber quality traits. The ANOVA for combined locations revealed significant Genotype x Location interactions for seven traits. Significant differences were observed among genotypes for all measured traits. Since the objective was to provide a comparison of the parental genotypes in order to show their agronomic and fiber quality parameters relative to three Indian cultivars, only averaged values for the parental genotypes will be provided, i.e., the significant Genotype x Location noted in the ANOVA will not be addressed.

The mean performances of these US lines were compared with three Indian developed cultivars. Phule 688 is included as central zone check which was released for the central zone of Indian cotton growing belt, including Aurangabad. NA1325 is a cultivar adapted to the south zone and used as zonal check for south India location Hyderabad. Suraj is high yielding cultivar that exhibits long SL, tolerance to sucking pests and included as a quality check for both the central and south zones. We considered Suraj as the Indian standard cultivar for discussion purposes (Table 6).

In this comparison, Suraj averaged 29.0 and 27.5 OVCNT and SDCNT respectively, 1623 kg ha^{-1} seed cotton yield with medium BOLWT of 3.4 g, 98.0 cm PLTHT and excellent GINNOT of 38.6%. Suraj produced an average SL of 30.9 mm and 223 kN m kg^{-1} fiber strength.

Suraj was significantly higher yielding than all US genotypes except UA48 (1543 kg ha^{-1}). Averaged over these Indian locations in 2015, Phule 688 significantly out yielded Suraj. UA48 out yielded NA1325 (1276 kg ha^{-1}) whereas LA 887 (1107 kg ha^{-1}), MD51 ne (1160 kg ha^{-1}), TAM 86 GGG-30 (1061 kg ha^{-1}) and TAM 88G-104 (1219 kg ha^{-1}) were not different than NA 1325. Thirty one of the US parental genotypes exhibited significantly more OVCNT than Suraj, which translated into higher SDCNT for 22 of the 31 (Table 6). Only DP50 and PD6520 was not different than Suraj for both OVCNT and SDCNT. Mebane averaged the highest absolute OVCNT at 34.2 which was not significantly higher than 17 of the remaining 32 US genotypes. Many of these are old or obsolete cultivars and may reflect an era of hand harvest in the US. The higher OVCNT appears to have generally resulted in higher SDCNT which theoretically, based on yield component relationships (Coyle and Smith 1997), should result in higher YLD, an assumption that does not hold when these genotypes were grown in India. Fifteen US genotypes exhibited larger BOLWT than Suraj, a trait that is a bit surprising since cotton is hand harvested in India and one would assume that larger bolls would be a selection criterion, even if concomitantly. The high yielding UA48 (a machine harvested cultivar in the US) exhibited higher OVCNT, SDCNT and higher BOLWT than the high yielding Suraj (a hand harvested cultivar). Other agronomic data from this comparison were that 21 US genotypes were shorter in PLTHT at maturity; 10 had greater GINOT and 5 exhibited heavier seeds as indicated by SDINX.

One US genotype (UA48) had significantly longer SL at 32.7 mm than Suraj at 30.9 mm, although seven others were not different than Suraj. None of the US genotypes exhibited greater STR than Suraj although 24 were not different. Eleven US genotypes exhibited better UR. All genotypes except TAM 73840 exhibited MIC values below the US standard range of 3.5 to 4.9 and two genotypes had significantly higher ELONG. No US genotype in this study was superior to Suraj in all categories.

Two additional Indian genotypes were included in this part of the dissertation study, those being Phule 688 and NA1325. Both of these were similar to many of the US genotypes in one or more measurements but it's notable that NA1325 was particularly low in STR and that the SDCNT data for Phule 688 must be in error because it is higher than OVCNT. Phule 688 averaged the highest YLD at 1928 kg ha^{-1} which was significantly higher than Suraj.

Many of the US genotypes averaged significantly higher OVCNT, SDCNT, BOLWT, GINOT, MIC, and less PLTHT than Suraj when grown across these locations in 2015. This suggests that these US genotypes could be used for introgression of these traits of interest. As India moves from large plants, from hand harvest, and from multiple harvests per year to machine harvest, reduced plant size, higher GINOT and superior fiber qualities are important criteria in future cultivars or hybrids.

Table 5. Mean squares from combined analysis of variance for indicated traits in upland cotton parental genotypes at Aurangabad and Hyderabad locations, India 2015.

S.O.V.	df	OVCNT †	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
Loc	1	183.10*	316.10**	4961928.10*	38.20*	186913.00**	0.98	0.19	1.38	675.80	1.54	4.58	9.25
Rep (loc)	4	19.50	2.50	324859.20	2.76	131.20	9.75	9.00	15.82	16005.20	1.86	29.02	1.27
Genotype	35	12.70**	8.70**	758499.70**	1.48**	294.60**	29.62**	4.40**	13.53**	1329.30**	0.36**	6.50**	0.16**
Gen*Loc	35	4.64*	10.50**	288751.00**	0.54**	91.73*	0.24	0.08	2.82**	133.42	0.06	1.60	0.05**
Error	140	2.96	4.30	37424.80	0.23	56.37	1.63	0.89	1.06	407.30	0.10	1.30	0.02
C.V. (%)		5.35	7.01	22.73	12.58	8.34	3.30	10.26	3.59	9.74	10.82	2.30	3.1

*Significant at P=0.05

** Significant at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g); SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

Table 6. Mean performance of select US upland cotton parental genotypes for indicated traits across Aurangabad and Hyderabad locations, India 2015.

Genotype	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
	(No)	(No)	(Kg ha^{-1})	(g)	(cm)	(%)	(g)	(mm)	(kN m kg^{-1})	(unit)	(Ratio)	(%)
Lone Star	33.8*	30.2*	271	3.6	92.3	41.5*	7.3	27.4	185.5	2.5	48.4*	5.1
Deltatype Webber	32.4*	29.9*	364	4.0*	88.7*	36.0	9.7	26.8	211.4	2.7	49.1*	5.3
Lightning Express	31.6*	29.7	678	3.2	93.0	35.7	8.3	26.7	177.8	2.8	49.8*	5.3
Mebane	34.2*	31.5*	608	4.0*	97.0	37.4	8.3	25.8	202.8	2.8	50.4*	5.4
Rex	31.5*	30.5*	529	4.1*	85.0*	35.4	8.8	27.7	184.4	2.9	47.6	5.3
Auburn 56	32.3*	30.5*	602	4.1*	85.3*	35.7	9.3	28.9	226.5	2.6	46.8	5.6
Stoneville 213	32.0*	28.3	641	4.1*	97.0	39.2	8.8	29.0	198.6	2.9	46.9	5.4
DP16	32.7*	28.7	665	4.0*	91.0	38.2	9.6	29.5	199.2	2.5	46.8	5.3
Delcot 277	33.4*	30.2*	884	3.9	90.3	42.1*	9.3	29.4	205.3	3.0	46.9	5.7
DES 422	33.2*	30.7*	713	3.5	94.7	42.6*	7.7	28.9	239.3	2.7	47.2	5.5
DP90	31.9*	30.8*	948	3.9	89.3*	38.7	8.6	29.4	214.3	3.1*	47.4	5.5
DP50	30.7	29.3	905	3.6	79.3*	36.9	8.5	30.4	199.7	2.9	46.9	5.6
SC1	32.0*	27.4	664	3.1	83.8*	40.1*	8.6	28.5	210.6	3.0	47.0	5.4
PD6520	28.8	26.2	593	3.2	89.3*	40.7*	9.7	28.4	195.1	2.8	47.4	5.3
CS8606	34.1*	30.2*	536	3.6	76.5*	39.6	8.6	26.2	178.7	2.7	49.7*	5.0
TAM 0155	33.6*	30.4*	835	4.3*	88.3*	39.1	9.7	27.3	204.4	2.8	48.5*	5.4
TAM 73840	33.3*	29.3	730	5.3*	80.7*	39.2	11.7*	28.1	191.4	3.6*	48.6*	5.4
LA 887	32.1*	31.6*	1107	4.5*	95.0	40.4*	8.7	29.9	218.7	2.8	47.2	5.5
MD 51ne	33.9*	30.8*	1160	3.9	96.3	39.9	9.0	29.1	202.8	2.9	47.4	5.5
Ciano Alamos 92	32.0*	30.6*	854	3.5	81.8*	41.0*	8.3	29.7	223.1	2.8	47.7	5.5
Ciano Cocorim 92	32.0*	29.3	939	3.7	85.2*	37.9	10.3*	28.6	226.9	3.1	47.4	5.5
TAM 86 GGG-30	32.1*	30.1*	1061	3.6	79.0*	40.5*	9.7	26.8	217.1	3.3*	49.0*	5.5
Acala Maxxa	33.4*	31.4*	449	4.5*	76.2*	38.4	10.0*	30.9	224.5	2.9	47.0	5.6

Table 6. Continued.

Genotype	OVCNT	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
	(No)	(No)	(Kg ha^{-1})	(g)	(cm)	(%)	(g)	(mm)	(kN m kg^{-1})	(unit)	(Ratio)	(%)
CS8601	32.2*	30.5*	760	3.6	81.2*	38.7	9.7	28.2	204.2	3.2*	48.0	5.3
Acala 1517-99	31.1*	30.7*	334	3.1	93.8	38.9	9.3	28.5	202.9	2.7	48.9*	5.4
GA 161	32.2*	29.9*	805	4.7*	97.3	37.7	10.3*	30.2	230.8	3.2*	47.1	5.9*
TAM 88G-104	32.0*	29.6	1219	4.3*	86.7*	39.7	9.3	28.4	200.9	3.1	47.9	5.5
Tamcot 73	33.6*	30.6*	1018	3.8	84.5*	41.0*	8.8	30.3	216.3	3.1*	46.9	5.9*
All Tex 7A21	31.0*	30.4*	880	3.6	93.0	43.5*	9.0	29.2	216.6	2.8	47.4	5.7
UA48	34.1*	30.2*	1545	4.6*	86.8*	38.0	9.6	32.7*	218.1	3.2*	46.5	5.7
Tamcot Sphinx	33.7*	29.4	688	4.0*	85.8*	35.2	9.7	27.7	207.1	3.2*	48.4*	5.6
TAM 94L-25	32.5*	30.4*	861	4.7*	79.2*	36.8	10.9*	30.6	208.1	3.0	46.1	5.3
PSC355	31.6*	28.2	939	3.6	89.2*	39.0	9.3	28.7	209.6	3.3*	48.3	5.8
Phule688	29.8	30.9*	1928*	3.7	104.5	33.6	9.7	26.6	195.8	3.1	49.4*	5.4
Suraj	29.0	27.5	1623	3.4	98.0	38.6	8.7	30.9	223.0	2.8	47.1	5.7
NA1325	28.6	28.6	1276	3.3	99.2	36.7	8.3	28.2	182.1	3.4*	46.8	5.3
LSD	1.96	2.36	220.03	0.55	8.54	1.45	1.07	1.17	22.96	0.36	1.30	0.16

*Significantly superior to Suraj at P=0.05.

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g); SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

Hybrid evaluations

The ANOVA for all genotypes in the study, 90 hybrids plus 30 lines plus 3 testers plus 3 Indian checks, indicated that the genotypes varied for all traits measured, verifying the choice of genotypes for this study (Table 4). Averaged across all genotypes, location significantly impacted OVCNT, SDCNT, YLD, BOLWT, and PLTHT but did not affect HVI fiber properties. The genotypes did not respond the same to the two locations in the study for OVCNT, SDCNT, YLD, BOLWT, PLTHT, SL, and ELONG as indicated by a significant Genotype x Location interaction; while this interaction was not significant for GINOT, SDINX, STR, MIC, or UR. For the seven traits where Genotype x Location interactions were significant will be discussed location wise while averaged means over locations will be discussed where Genotype x Location interactions were found non-significant. The twelve measured traits will be discussed below as three categories, boll, agronomic and fiber properties.

A) Boll Parameters:

Among OVCNT, SDCNT, BOLWT and SDINX, which were grouped as boll parameters OVCNT, SDCNT and BOLWT had significant Genotype x Location interaction, hence location wise results presented (Table 7). For SDINX, means and heterosis combined over locations were calculated (Table 8), since Genotype x Location was non-significant.

OVCNT when grown at AWB ranged from 31.0 to 36.6, with 89 of the 90 hybrids exhibiting significantly more ovules per boll than Suraj (30.7) (Table 7). At HYD, OVCNT ranged from 28.8 to 33.7 with 24 F_1 genotypes significantly exceeding

Suraj (29.4). Heterobeltiosis for OVCNT ranged from -11.1% to 7.5% and -10.9% to 7.4 % at AWB and HYD, respectively. Heterobeltiosis was calculated over best parent. For example, hybrid Lone Star /Tamcot Sphinx had 36.6 OVCNT while parents Lone Star and Tamcot Sphinx exhibited 36.0 and 35.2 ovules per boll, respectively. As discussed in the material and methods, heterobeltiosis was derived by [(36.6-36)/36]*100=1.9%. For forty and 52 hybrids significant heterobeltiosis (significantly different than zero) was recorded at AWB and HYD, respectively; ten and nine genotypes had positive heterobeltiosis across all three testers at these locations. These 19 F_1 combinations suggest that different parental combinations may result in hybrid vigor for OVCNT which theoretically would result in more seeds per boll and thus more lint per boll. Closer scrutiny of the data reveals the complexity of the value of heterobeltiosis for this trait. At AWB, TAM 94L-25 combined with six lines for significant and positive heterobeltiosis for OVCNT and only twice for significant and negative results. However, at HYB, PSC355 was the tester that combined most often for positive and significant heterobeltiosis, five positive and one negative.

Correlation analysis showed significant positive correlation between OVCNT and SDCNT at both locations (r=0.37 for AWB and r=0.41 for HYD). SDCNT ranged from 28.1 to 35.6 at AWB, and 24.7 to 31.8 at HYD (Table 7). Unlike results for OVCNT at AWB, only two F_1 genotypes averaged higher SDCNT than Suraj (30.5) while 57 hybrids exhibited significantly higher SDCNT at HYD as compared to Suraj (26.7), which appears to be a result of a low SDCNT for Suraj at HYD rather than higher SDCNT among the hybrids. Heterobeltiosis for SDCNT was from -9.4% to 14.4% and -

20.4% to 10.3% at AWB and HYD, respectively. Thirty eight among 57 significant F_1 hybrids revealed positive heterobeltiosis at AWB while seven among 30 hybrids were found positively significant at the HYD location. Five genotypes at AWB and 11 at HYD recorded greater SDCNT than OVCNT, which must be a sampling error or sampling anomaly.

BOLWT, which is an important yield component ranged between 3.1 g and 4.9 g at AWB (Table 7). Seventy three hybrids averaged significant and superior BOLWT as compared to Suraj at 2.7 g. At the HYD location, overall higher BOLWTs were recorded, which ranged from 3.8 g to 6.3 g. Forty one F_1 hybrids were significantly higher in BOLWT than the Indian cultivar Suraj at 4.1 g. Heterobeltiosis at AWB for BOLWT ranged from -23.8% to 24.2% with 21 of 38 genotypes with significant heterobeltiosis exhibiting heterosis for this trait relative to the high parent. Heterobeltiosis at HYD ranged from -24.8% to 34.0% with 26 F_1 genotypes recording positive significant heterosis.

The variability and apparent randomness of heterobeltiosis among the F_1s of these lines and testers suggest that hybrid vigor for these boll parameters would be serendipitous rather than a planned event in a cotton breeding program. However, it appears logical the breeders could begin that process by selecting for OVCNT but the significant location effect also makes it tenuous selection criteria to which a breeder should devote time.

SDINX, weight per 100 seeds, ranged between 7.7 g to 11.3 g (Table 8). Significant heterobeltiosis (range from -29.8% to 17.2% above the best parent) was observed for 35 F_1 genotypes but only two hybrid combinations resulted in heterobeltiosis values that were positive and significant. These were Deltatype Webber/Tamcot Sphinx and TAM 0155/PSC355. Both of these lines are obsolete and the testers are more recent obsolete cultivars. Breeders of machine harvested upland cotton cultivars generally try to maximize GINOT in which reduced SDINX is usually a primary component. While two data points are not sufficient to draw conclusions, both of these F_1s averaged low GINOT as would be expected.

Table 7. Mean performance and heterobeltiosis based on best performing parent for 90 upland cotton hybrids for boll properties grown at Aurangabad or Hyderabad, India, 2015.

Hybrid Combination	AWB		HYD		AWB		HYD		AWB		HYD	
	OVCNT†	Hb%‡	OVCNT	Hb%	SDCNT	Hb%	SDCNT	Hb%	BOLWT	Hb%	BOLWT	Hb%
	(No)		(No)		(No)		(No)		(g)		(g)	
Lone Star/ Sphinx	36.6*	1.9	31.7	-1.3	33.2	-1.0	30.5*	0.7	4.1*	24.2**	6.2*	32.6**
Lone Star/94L-25	36.1*	0.4	31.7	-2.0	35.6*	6.0**	30.8*	-0.5	4.0*	-4.8	5.6*	9.8*
Lone Star/PSC355	34.9*	-2.9*	31.2	-1.5	31.9	-5.1**	29.7*	6.7*	3.5*	10.4*	4.2	-1.6
Deltatype Webber/Sphinx	35.3*	0.4	31.9	-1.0	32.0	5.1**	29.5*	-2.6	3.9*	19.2**	4.2	-9.9
Deltatype Webber/94L-25	33.8*	3.4*	32.5*	0.7	31.5	3.6*	29.8*	-3.8	4.4*	5.6	4.9	-3.9
Deltatype Webber/PSC355	33.5*	2.2	30.4	-5.6**	32.7	7.3**	30.5*	4.0	3.1	-5.1	4.5	-2.2
Lightning Express/ Sphinx	33.8*	-4.1**	29.8	-7.2**	30.3	-1.1	27.2	-10.3**	3.1	-5.1	4.4	-6.4
Lightning Express/94L-25	33.9*	3.6*	29.3	-9.2**	31.3	2.2	25.0	-19.4**	3.2	-23.8**	5.1*	0.0
Lightning Express/PSC355	33.1*	1.0	31.3	0.0	32.8	7.0**	29.0	1.2	3.7*	15.6**	4.5	10.6
Mebane/Sphinx	34.0*	-3.3*	31.8	-4.0**	31.4	-3.5*	31.3*	2.7	3.8*	5.6	4.7	0.0
Mebane/94L-25	33.3*	-5.5**	33.3*	0.7	33.2	2.0	30.0*	-3.2	3.9*	-7.1*	5.4*	6.5
Mebane/PSC355	35.7*	1.3	32.4*	-2.2	33.6	3.1*	30.7*	0.5	3.7*	3.7	4.5	1.5
Rex/Sphinx	33.7*	-4.4**	31.8	-1.0	32.9	5.0**	30.0*	-1.0	4.0*	20.2**	5.2*	5.4
Rex/94L-25	34.2*	4.5**	30.8	-4.6**	30.5	-2.6	30.7*	-1.1	4.4*	5.6	5.3*	3.9
Rex/PSC 355	32.9*	0.2	31.9	1.5	30.8	-1.8	28.7	-3.4	3.3	2.1	5.1*	3.4
Auburn 56/Sphinx	34.3*	-2.6	31.1	-4.5**	32.2	8.2**	29.0	-7.0**	4.0*	21.0**	4.8	-2.7
Auburn 56/94L-25	34.3*	5.0**	32.0	-1.7	31.8	6.2**	31.0*	-0.5	3.9*	-6.3	5.6*	10.5*
Auburn 56/PSC355	34.6*	5.6**	30.8	-5.5**	31.8	6.0**	31.0*	-0.5	3.5*	6.0	4.7	-4.1
Stoneville 213/Sphinx	34.9*	-0.9	29.9	-7.0**	32.6	13.8**	31.7*	4.5	3.6*	-6.0	4.4	-6.4
Stoneville 213/94L-25	34.1*	-1.3	33.2*	2.8	32.2	7.7**	30.3*	-2.2	3.6*	-15.1**	5.9*	15.7**
Stoneville 213/PSC355	34.1*	-1.4	31.7	4.5**	30.3	1.1	26.0	-6.6*	3.4	-11.2**	4.5	4.7
DP16/ Sphinx	34.6*	-1.6	31.1	-3.1*	31.0	-3.8**	31.3*	3.4	3.8*	-0.9	5.2*	11.3*
DP16/94L-25	33.5*	-1.6	30.0	-7.0**	31.6	-2.1	25.5	-17.7**	4.2*	-0.8	4.6	-9.2
DP16/PSC355	33.2*	-2.4	32.2*	2.4	33.4	3.7**	27.0	-2.9	4.0*	4.3	4.7	15.4**
Delcot 277/ Sphinx	33.0*	-6.3**	29.6	-7.9**	29.7	-1.4	30.2*	-0.5	3.8*	4.6	4.3	-7.8
Delcot 277/94L-25	34.6*	-1.2	31.5	-2.4	31.5	4.5**	29.3	-5.4*	4.1*	-3.2	6.3*	23.5**
Delcot 277/PSC355	34.0*	-2.9*	30.7	-3.2*	30.8	2.3	30.7*	1.1	4.0*	11.0**	4.7	13.6*
DES 422/ Sphinx	34.5*	-2.1	31.0	-3.3*	32.0	-0.7	30.0*	-1.0	3.3	1.0	5.1*	9.2
DES 422/ 94L-25	33.6*	-2.7	28.8	-10.9**	32.1	-0.4	30.5*	-1.6	3.8*	-10.3**	3.8	-24.8**
DES 422/PSC355	33.5*	-2.9*	31.2	-1.7	31.2	-3.2*	29.8*	2.3	3.6*	12.5**	5.1*	23.6**
DP90/Sphinx	33.8*	-4.0**	30.0	-8.3**	33.3	6.3**	31.3*	3.3	3.8*	6.5	5.5*	17.0**
DP90/ 94L-25	33.3*	1.9	30.8	-5.8**	30.2	-3.5*	30.5*	-1.6	3.9*	-6.3	6.1*	20.3**
DP90/PSC355	33.6*	2.4	30.9	-5.4**	30.2	-3.5*	29.3	-3.3	3.5	-2.8	4.3	2.4

Table 7. Continued.

Hybrid Combination	AWB		HYD		AWB		HYD		AWB		HYD	
	OVCNT†	Hb%‡	OVCNT	Hb%	SDCNT	Hb%	SDCNT	Hb%	BOLWT	Hb%	BOLWT	Hb%
	(No)		(No)		(No)		(No)		(g)		(g)	
DP50/Sphinx	33.4*	-5.2**	29.6	-7.7**	32.2	3.9**	28.0	-7.6**	3.7*	4.8	4.3	-7.8
DP50/ 94L-25	34.0*	4.1**	31.8	-1.7	32.9	6.1**	31.0*	0.0	3.8*	-10.3**	5.3*	3.3
DP50/PSC355	31.9*	-2.6	32.4*	6.8*	32.2	4.0**	29.8*	7.3**	3.2	-7.6	4.7	13.8*
SC1/ Sphinx	32.9*	-6.6**	31.1	-3.1*	30.3	-4.8**	27.0	-10.9**	3.8*	14.1**	4.5	-4.3
SC1/ 94L-25	32.9*	-6.2**	33.2*	2.8	32.6	2.2	30.8*	-0.5	3.9*	-7.1*	5.0*	-1.3
SC1/PSC355	33.3*	-4.9**	32.5*	7.4**	31.9	0.1	28.2	1.3	3.4	3.1	3.9	-4.9
PD6520/ Sphinx	31.7*	-9.9**	31.0	-3.4*	32.0	7.0**	28.0	-7.6**	3.7*	12.1**	4.3	-9.2
PD6520/ 94L-25	32.1*	-1.8	29.8	-7.7**	30.3	1.4	24.7	-20.4**	3.9*	-7.1*	5.0*	-2.0
PD6520/PSC355	33.4*	1.9	29.1	-4.0*	31.9	6.3**	28.3	1.9	3.8*	16.2**	4.5	10.6
CS8606/ Sphinx	34.7*	-2.1	31.7	-3.1*	32.2	4.3**	28.7	-5.4*	4.0*	20.2**	3.9	-16.3**
CS8606/ 94L-25	35.3*	-0.5	32.4*	-0.7	33.4	8.0**	29.2	-5.9*	3.9*	-7.1*	5.9*	16.3**
CS8606/PSC355	34.4*	-2.8*	32.1	-1.6	28.1	-9.1**	31.0*	5.1*	3.4	3.0	4.4	7.3
TAM 0155/Sphinx	31.3*	-11.1**	32.9*	2.1	33.4	0.5	30.0*	-1.0	3.7*	-6.0	5.6*	18.4**
TAM 0155/ 94L-25	34.7*	-0.5	32.7*	1.2	32.0	-3.6**	30.7*	-1.1	4.3*	2.4	5.6*	10.5*
TAM 0155/PSC355	33.4*	-4.3**	31.7	-1.8	32.3	-2.6	30.7*	10.3**	4.1*	5.1	4.8	4.3
TAM 73840/ Sphinx	33.7*	-4.3**	32.6*	1.5	31.0	3.7*	30.8*	1.8	4.0*	-15.5**	4.7	-19.4**
TAM 73840/ 94L-25	32.7*	-6.2**	33.7*	4.2**	31.5	5.2**	31.0*	0.0	4.9*	5.0	4.6	-21.7**
TAM 73840/PSC355	35.8*	2.7	30.4	-3.9*	32.1	7.1**	29.7*	3.5	3.6*	-23.2**	5.6*	-3.4
LA 887/ Sphinx	32.7*	-7.2**	31.6	-1.7	31.3	-4.9**	29.8*	-1.6	3.8*	3.6	5.3*	0.6
LA 887/94L-25	34.4*	5.3**	33.0*	2.2	33.4	1.6	30.5*	-1.6	4.0*	-5.6	5.2*	-1.9
LA 887/PSC355	32.7*	-0.3	32.9*	3.9*	30.9	-6.1**	30.0*	-1.1	3.6*	-1.8	4.5	-15.7**
MD 51ne/ Sphinx	35.0*	-0.7	31.4	-4.6**	32.5	-0.2	31.5*	4.0	3.2	-2.0	6.3*	34.0**
MD 51ne/ 94L-25	32.9*	-5.7**	32.2*	-1.9	32.3	-0.7	30.8*	-0.5	4.3*	2.4	5.2*	1.3
MD 51ne/PSC355	33.6*	-3.8**	30.8	-6.3**	30.2	-7.1**	29.0	0.0	3.4	6.2	4.5	-1.4
Ciano Alamos 92/ Sphinx	33.2*	-5.7**	31.0	-3.4*	31.2	-5.4**	29.3	-3.2	4.2*	23.8**	5.2*	9.9
Ciano Alamos 92/ 94L-25	33.4*	-0.5	30.5	-5.7**	33.0	-0.1	26.5	-14.5**	4.5*	7.9*	4.9	-3.9
Ciano Alamos 92/PSC355	33.4*	-0.5	32.7*	7.2**	31.9	-3.4*	28.8	2.4	4.0*	19.8**	4.3	4.9
Ciano Cocorim 92/ Sphinx	33.5*	-4.7**	30.5	-5.2**	30.2	-3.9**	31.3*	3.4	4.0*	12.0**	5.4*	14.2**
Ciano Cocorim 92/94L-25	31.0	-5.2**	33.4*	3.5*	31.9	1.5	31.8*	2.7	4.4*	5.6	5.6*	10.5*
Ciano Cocorim 92/PSC355	33.6*	2.4	30.8	-4.5**	32.8	4.3**	30.7*	10.3**	3.5*	-2.8	4.7	14.6*
TAM 86 GGG-30/ Sphinx	33.0*	-6.3**	31.3	-2.4	30.7	-2.9*	29.0	-4.3	3.9*	4.5	5.4*	14.9**
TAM 86 GGG-30/94L-25	32.8*	0.2	32.6*	0.8	32.6	3.2*	28.8	-7.0**	4.3*	2.4	5.6*	10.5*
TAM 86 GGG-30/PSC355	33.4*	1.9	30.9	-3.4*	33.3	5.6**	29.7*	3.5	3.7*	-1.8	5.1*	23.6**

Table 7. Continued.

Hybrid Combination	AWB		HYD		AWB		HYD		AWB		HYD	
	OVCNT†	Hb%‡	OVCNT	Hb%	SDCNT	Hb%	SDCNT	Hb%	BOLWT	Hb%	BOLWT	Hb%
	(No)		(No)		(No)		(No)		(g)		(g)	
Acala Maxxa/ Sphinx	33.6*	-4.5**	30.8	-5.7**	32.8	2.1	29.2	-4.9*	3.9*	11.3**	5.0	-9.1*
Acala Maxxa/94L-25	33.2*	-2.7	32.7*	0.0	31.9	-0.7	30.2*	-2.7	4.0*	-5.6	6.1*	12.2**
Acala Maxxa/PSC355	34.4*	0.7	30.7	-6.1**	32.0	-0.3	30.5*	-0.5	3.3	-6.6	5.8*	6.1
CS8601/ Sphinx	34.4*	-2.4	31.9	-0.6	30.8	1.9	27.7	-10.3**	3.4	-8.9*	4.4	-6.4
CS8601/ 94L-25	34.4*	5.3**	31.5	-2.6	33.3	10.3**	29.5*	-4.8*	4.2*	-0.8	4.7	-8.5
CS8601/PSC355	33.2*	1.1	29.5	-7.9**	32.9	8.8**	29.3	-4.9*	3.4	-9.8**	5.1*	23.6**
Acala 1517-99/ Sphinx	34.5*	-2.0	31.0	-3.4*	34.5*	14.4**	28.5	-8.6**	3.6*	9.1*	4.2	-11.3*
Acala 1517-99/ 94L-25	32.0*	-2.0	31.7	-2.0	32.2	6.9**	28.5	-8.6**	3.3	-20.6**	5.3*	3.9
Acala 1517-99/PSC355	33.7*	2.7	31.0	0.0	31.6	4.8**	30.3*	-2.7	3.1	-6.1	4.1	0.0
GA 161/ Sphinx	34.4*	-2.4	30.8	-4.0**	30.3	1.4	30.2*	-0.4	3.6*	-2.7	5.5*	-2.4
GA 161/ 94L-25	35.5*	7.5**	29.6	-8.3**	33.6	12.3**	29.7*	-4.3	4.3*	2.4	4.4	-21.3**
GA 161/PSC355	33.7*	2.0	32.5*	3.3*	31.1	3.7*	30.5*	2.2	3.7*	0.0	5.2*	-8.3
TAM 88G-104/ Sphinx	34.6*	-1.7	30.7	-4.5**	33.8	5.3**	30.3*	0.1	3.9*	3.5	4.7	0.7
TAM 88G-104/ 94L-25	34.4*	2.6	30.5	-5.5**	31.7	-1.3	30.8*	-0.5	4.0*	-4.0	6.1*	19.0**
TAM 88G-104/PSC355	33.5*	0.1	32.7*	7.3**	32.3	0.7	29.8*	7.3**	3.7*	-1.8	4.6	-2.1
Tamcot 73/ Sphinx	35.4*	0.5	30.2	-7.2**	32.7	0.7	31.2*	2.9	3.9*	16.8**	4.3	-7.8
Tamcot 73/94L-25	35.3*	2.2	32.1	-1.3	33.5	3.2*	30.7*	-1.1	3.8*	-8.7**	5.2*	2.6
Tamcot 73/PSC355	32.8*	-5.1**	30.1	-7.5**	31.1	-4.1**	27.3	-5.2*	4.0*	19.8**	4.5	7.1
All Tex 7A21/ Sphinx	33.5*	-4.7**	29.9	-6.9**	33.1	8.2**	28.5	-5.9*	3.8*	16.2**	4.9	5.0
All Tex 7A21/ 94L-25	32.3*	-1.3	32.0	-0.9	29.3	-4.2**	29.7*	-4.3	3.9*	-7.9*	4.7	-7.8
All Tex 7A21 /PSC355	33.7*	2.6	30.6	0.8	31.3	2.3	29.2	-3.3	3.5*	7.1	4.8	16.3**
UA48/ Sphinx	32.9*	-6.6**	30.9	-8.5**	28.9	-9.4**	28.8	-4.8*	4.2*	5.8	4.9	-5.1
UA48/TAM 94L-25	35.8*	4.0**	33.1*	-1.9	31.3	-1.7	31.7*	2.2	4.4*	5.6	5.1*	-2.6
UA48/PSC355	34.3*	-0.6	32.9*	-2.6	31.1	-2.4	30.0*	5.3*	3.6*	-10.0**	4.7	-10.3*
Suraj (check)	30.7		29.4		30.5		26.7		2.7		4.1	

*Significant to Suraj at P=0.05 (For mean comparison with Suraj and heterosis different than zero)
** Significant to Suraj at P=0.01 (For mean comparison with Suraj and heterosis different than zero)
† OVCNT=No of ovules per boll; SDCNT=No of seeds per boll; BOLWT=Boll weight (g);
‡ Hb%= heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25, AWB=Aurangabad, HYD=Hyderabad

Table 8. Mean performance and heterobeltiosis based on best performing parent for 90 upland cotton hybrids for indicated traits. Means averaged over Aurangabad and Hyderabad, India, 2015.

Hybrid Combination	SDINX† (g)	Hb%‡	GINOT (%)	Hb%
Lone Star/ Sphinx	8.5	-12.1**	40.0	-3.5
Lone Star/94L-25	9.3*	-15.3**	39.0	-5.9*
Lone Star/PSC355	7.7	-17.9**	40.9*	-1.2
Deltatype Webber/Sphinx	10.6*	9.5*	36.1	0.5
Deltatype Webber/94L-25	11.0*	0.8	36.2	-1.7
Deltatype Webber/PSC355	9.6	-0.9	39.6	1.6
Lightning Express/ Sphinx	8.3	-13.8**	38.8	8.5**
Lightning Express/94L-25	7.7	-29.8**	37.2	1.1
Lightning Express/PSC355	9.3	0.0	39.3	0.8
Mebane/Sphinx	9.0	-6.9	39.8	6.2*
Mebane/94L-25	10.3*	-5.3	38.9	4.0
Mebane/PSC355	8.1	-13.4**	39.8	2.0
Rex/Sphinx	10.0*	3.4	38.6	9.0**
Rex/94L-25	10.7*	-2.3	37.6	2.0
Rex/PSC355	9.9*	6.3	39.1	0.3
Auburn 56/Sphinx	9.9*	2.6	38.0	6.4*
Auburn 56/94L-25	9.7	-11.5**	36.4	-1.0
Auburn 56/PSC355	8.3	-11.6**	38.6	-0.9
Stoneville 213/Sphinx	9.3	-3.4	40.5*	3.3
Stoneville 213/94L-25	9.6	-12.2**	38.0	-3.1
Stoneville 213/PSC355	9.7	3.6	42.2*	7.7**
DP16/ Sphinx	9.3	-3.4	39.7	4.1
DP16/94L-25	11.0*	0.8	37.6	-1.6
DP16/PSC355	9.7	0.9	37.1	-4.9
Delcot 277/ Sphinx	10.3*	6.9	38.6	-8.4**
Delcot 277/94L-25	10.0*	-8.4*	38.5	-8.5**
Delcot 277/PSC355	9.8	4.5	38.0	-9.8**
DES 422/ Sphinx	8.7	-10.3*	41.1*	-3.6
DES 422/ 94L-25	9.2	-16.0**	40.6*	-4.6*
DES 422/PSC355	8.6	-8.0	39.4	-7.5**
DP90/Sphinx	8.7	-10.3*	38.6	-0.1
DP90/ 94L-25	9.0	-17.6**	39.2	1.5
DP90/PSC355	9.0	-3.6	39.5	1.4

Table 8. Continued.

Hybrid Combination	SDINX (g)	Hb%	GINOT (%)	Hb%
DP50/Sphinx	9.0	-6.9	37.7	2.4
DP50/ 94L-25	10.0*	-8.4*	38.5	4.5
DP50/PSC355	8.6	-8.0	38.9	-0.3
SC1/ Sphinx	8.9	-7.8	40.5*	1.1
SC1/ 94L-25	10.3*	-6.1	39.1	-2.5
SC1/PSC355	9.7	3.6	41.4*	3.3
PD6520/ Sphinx	9.3	-3.4	39.1	-3.7
PD6520/ 94L-25	10.7*	-2.3	39.5	-2.7
PD6520/PSC355	9.7	0.0	39.2	-3.5
CS8606/ Sphinx	10.0*	3.4	39.6	0.1
CS8606/ 94L-25	10.0*	-8.4*	38.2	-3.4
CS8606/PSC355	9.3	0.0	40.6*	2.5
TAM 0155/Sphinx	9.7	0.0	40.5*	3.7
TAM 0155/ 94L-25	10.3*	-5.3	39.7	1.7
TAM 0155/PSC355	11.3*	17.2**	37.5	-3.9
TAM 73840/ Sphinx	10.6*	-9.3*	38.8	-1.0
TAM 73840/ 94L-25	11.3*	-3.6	38.2	-2.6
TAM 73840/PSC355	9.6*	-17.9**	39.3	0.3
LA 887/ Sphinx	8.7	-10.3*	41.5*	2.9
LA 887/94L-25	9.8*	-9.9*	39.0	-3.4
LA 887/PSC355	8.8	-5.4	40.0	-0.9
MD 51ne/ Sphinx	8.7	-10.3*	40.4*	1.0
MD 51ne/ 94L-25	10.7*	-2.3	38.5	-3.6
MD 51ne/PSC355	8.7	-7.1	39.4	-1.4
Ciano Alamos 92/ Sphinx	9.0	-6.9	39.8	-3.0
Ciano Alamos 92/ 94L-25	10.0*	-8.4*	37.7	-8.1**
Ciano Alamos 92/PSC355	9.3	0.0	41.2*	0.4
Ciano Cocorim 92/ Sphinx	9.3	-9.7*	40.0	5.7*
Ciano Cocorim 92/94L-25	10.0*	-8.4*	38.2	0.8
Ciano Cocorim 92/PSC355	10.6*	2.4	40.4*	3.6
TAM 86 GGG-30/ Sphinx	9.0	-6.9	37.2	-8.1**
TAM 86 GGG-30/94L-25	10.7*	-2.3	35.0	-13.4**
TAM 86 GGG-30/PSC355	9.6	-0.9	36.0	-10.9**

Table 8. Continued.

Hybrid Combination	SDINX (g)	Hb%	GINOT (%)	Hb%
Acala Maxxa/ Sphinx	8.7	-13.3**	41.7*	8.4**
Acala Maxxa/94L-25	10.3*	-6.1	40.0	4.0
Acala Maxxa/PSC355	8.7	-13.3**	39.8	2.0
CS8601/ Sphinx	9.0	-6.9	38.7	0.0
CS8601/ 94L-25	9.6*	-12.2**	39.1	1.0
CS8601/PSC355	8.7	-10.3*	38.4	-1.4
Acala 1517-99/ Sphinx	9.0	-6.9	40.5*	4.0
Acala 1517-99/ 94L-25	9.3*	-14.5**	39.9	2.6
Acala 1517-99/PSC355	9.0	-3.6	40.5*	4.0
GA 161/ Sphinx	10.0*	-3.2	40.4*	7.1**
GA 161/ 94L-25	10.5*	-3.8	36.4	-3.3
GA 161/PSC355	10.0*	-3.2	39.7	1.9
TAM 88G-104/ Sphinx	8.6	-11.2*	40.8*	2.9
TAM 88G-104/ 94L-25	11.2*	2.3	39.4	-0.7
TAM 88G-104/PSC355	8.8	-6.2	40.1	1.0
Tamcot 73/ Sphinx	9.3*	-3.4	41.0*	0.0
Tamcot 73/94L-25	9.3*	-15.3**	36.6	-10.6**
Tamcot 73/PSC355	9.0	-3.6	40.7*	-0.6
All Tex 7A21/ Sphinx	9.0	-6.9	41.9*	-3.6
All Tex 7A21/ 94L-25	9.7*	-11.5**	42.0*	-3.4
All Tex 7A21 /PSC355	8.3	-10.7*	40.7*	-6.4**
UA48/ Sphinx	9.7*	0.0	39.7	4.4
UA48/TAM 94L-25	10.3*	-5.3	37.6	-1.1
UA48/PSC355	9.3*	-2.6	38.8	-0.5
Suraj	8.7		38.6	

*Significant to Suraj at P=0.05 (For mean comparison with Suraj and heterosis different than zero)
** Significant to Suraj at P=0.01 (For mean comparison with Suraj and heterosis different than zero)
† SDINX= Seed index (g); GINOT=Ginning out turn (%)
‡ Hb% i.e. heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25

B) Agronomic traits:

Plant height (PLTHT), seed cotton yield (YLD) and gin out turn (GINOT) were considered as agronomic traits. Genotype x Location interactions were significant for PLTHT and YLD while not significant for GINOT (Table 4). Reduced PLTHT will be important as India moves to mechanical harvest and breeders will need to select parents that will produce progeny with reduced plant size but with improved yield potential. The lowest PLTHT of 100 cm was recorded for TAM 0155/Tamcot Sphinx while Acala 1517-99/PSC355 was the tallest at 143.3 cm, although not significantly taller than Suraj, at AWB (Table 9). Fifteen hybrids exhibited significantly shorter PLTHT than Suraj (130 cm) and four of those exhibited desired significant negative heterobeltiosis. Both of these results are desirable for developing more compact hybrid plants for mechanical harvest in India. Heterobeltiosis for PLTHT was -13.0% to 28.8%. Tamcot Sphinx appears to be a good parent for reducing plant height since nine of the 30 hybrids with Sphinx were significantly shorter than best (shortest) parent. PLTHT was lower at HYD than at AWB ranging between 48.0 cm and 71.3 cm. Thirty six hybrids had significantly lower PLTHT compared to Suraj (66.0 cm) and none were taller. Heterobeltiosis for PLTHT ranged from -19.3% to 33.8%. Sixteen hybrids with Tamcot Sphinx had significant shorter PLTHT than Suraj at HYD and eight of these had significant and negative heterobeltiosis. This indicates that short genotypes can be bred without much compromise on yield through using suitable US germplasm like Tamcot Sphinx in India.

At AWB, YLD of the F_1 hybrids ranged from 755 kg ha^{-1} (Acala 1717-99/PSC355) to 1994 kg ha^{-1} (UA48/Tamcot Sphinx), while heterobeltiosis ranged from -

34.2% (Acala 1717-99/PSC355) to 136.7% (Rex/Tamcot Sphinx) (Table 9). Thirty-eight and seven F_1 hybrids were found to have positive and negative significant heterosis, respectively, across all three testers. Twenty-six Tamcot Sphinx combinations were significantly positive for heterosis over best parent and twelve entries among 90 F_1 hybrids yielded significantly superior to the in-country control, Suraj.

Similarly, at HYD, YLD ranged from 306 kg ha^{-1} (CS8606/Tamcot Sphinx) to 1125 kg ha^{-1} (Tamcot 73/PSC355) and none of the 90 F_1 genotypes were found superior or equal to Suraj (2059 kg ha^{-1}) (Table 9). Unlike the AWB location, at HYD, UA48/Tamcot Sphinx (-56.0%) was significantly lower yielding that Suraj and exhibited poor heterobeltiosis at 56% below the best yielding parent. All Tex 7A21/Tamcot Sphinx (75.8%) had highest positive and significant heterobeltiosis although this hybrid yielded significantly less than the Indian control. A total of 36 hybrids across all three testers exhibited significant heterobeltiosis; nineteen among them exhibited positive heterosis over best parent. Three F_1 hybrids, All Tex 7A21 /Tamcot Sphinx, GA 161/Tamcot Sphinx and Lightning Express/PSC355 had positive and significant heterosis at both locations. Also, particular combinations of US lines and testers appear to indicate that specific F_1 hybrid made from US cultivars or released germplasm lines would produce hybrids competitive with India's high yielding Suraj. Those were UA48, GA 161, TAM88G104 and Tamcot 73.

Significant heterosis observed in this study suggests that F_1 cultivar hybrids using US parental material may be useful in developing hybrid cultivars for high density planting conditions in India. However, choice of parents will be a critical consideration as indicated by the three testers in this study.

Gin out turn, an important trait for ginners to retrieve higher lint yield through ginning of raw seed cotton, ranged between 35.0% and 42.2 % while heterosis over the high parent ranged between -13.4% to 9.0% (Table 8). Mean performance of twenty three entries were superior to check cultivar Suraj (38.6%). Seven of 90 F_1 genotypes produced positive and superior heterosis and five of the seven had Tamcot Sphinx as one parent indicating breeding value of this parental line to increase GINOT apart from yield.

C) Fiber quality traits:

Fiber qualities are important since India and the US both export the majority of the upland cotton produced. To be competitive in the international market, quality standards must be maintained. In this experiment, US lines, testers, and F_1 hybrids based on these parental lines were tested in India under high density conditions with the objective to study the effect of environment on specific traits, especially fiber quality, and identify better performing parents. Since SL and ELONG had significant Genotype x Location interaction, location wise mean performance of F_1 hybrids compared to the local check Suraj, and heterosis over best parent estimated are presented in Table 10. For STR, MIC, and UR, where Genotype x Location interaction was non-significant, average performance over two locations is presented in Table 11.

Table 9. Mean performance and heterobeltiosis based on best performing parent for 90 upland cotton hybrids for agronomic properties grown at Aurangabad or Hyderabad, India, 2015.

Hybrid Combination	AWB		HYD		AWB		HYD	
	PLTHT†	Hb%‡	PLTHT	Hb%	YLD	Hb%	YLD	Hb%
	(cm)		(cm)		(kg ha^{-1})		(kg ha^{-1})	
Lone Star/ Sphinx	118.3	2.9	64.0	4.3	1319	75.6**	522	-16.6
Lone Star/94L-25	123.3	17.5**	61.0	14.4**	893	-11.3	680	-5.1
Lone Star/PSC355	133.3	14.3**	65.7	7.1*	781	-31.9**	494	-32.7**
Deltatype Webber/Sphinx	116.7	1.4	67.0	10.4**	1069	42.3**	352	-43.8**
Deltatype Webber/94L-25	121.7	15.9**	59.3	11.3**	889	-11.6	490	-31.6*
Deltatype Webber/PSC355	125.0	7.1**	55.0*	-9.3**	977	-14.8	589	-19.7
Lightning Express/ Sphinx	123.3	7.2**	67.7	2.5	1608*	114.2*	733	17.0
Lightning Express/94L-25	125.0	19.0**	60.7	13.8**	918	-8.8	1011	41.0**
Lightning Express/PSC355	128.3	10.0**	71.3	15.6**	1403	22.3*	968	32.1**
Mebane/Sphinx	120.0	4.3	51.7*	-19.3**	1343	52.6**	407	-35.0*
Mebane/94L-25	116.7	11.1**	55.3*	3.8	958	-4.7	763	6.4
Mebane/PSC355	131.7	12.8**	59.7	-3.3	1280	11.6	564	-23.1
Rex/Sphinx	111.7*	-2.9	49.3*	-13.0**	1778*	136.7*	658	5.1
Rex/94L-25	126.7	20.6**	51.0*	-4.3	1284	27.7*	627	-12.6
Rex/PSC355	126.7	10.1**	62.7	13.9**	1141	-0.5	799	9.0
Auburn 56/Sphinx	125.0	10.3**	51.3*	-10.5**	1358	80.9**	602	-3.8
Auburn 56/94L-25	116.7	11.1**	62.7	17.6**	987	-1.9	903	26.0**
Auburn 56/PSC355	125.0	10.3**	63.7	11.0**	1200	4.6	955	30.3**
Stoneville 213/Sphinx	133.3	15.9**	57.7	-16.4**	1317	75.3**	668	6.8
Stoneville 213/94L-25	126.7	20.6**	61.7	15.7**	1208	20.1	951	32.6**
Stoneville 213/PSC355	126.7	8.5**	55.0*	-10.9**	1182	3.1	604	-17.6
DP16/ Sphinx	120.0	4.3	58.3	-0.6	1529	67.4**	714	14.1
DP16/94L-25	121.7	15.9**	54.3*	1.9	1041	3.5	844	17.7
DP16/PSC355	125.0	7.1**	57.7	-1.7	1110	-3.2	726	-0.9
Delcot 277/ Sphinx	106.7*	-7.2**	61.0	7.6*	1554	36.0**	649	3.5
Delcot 277/94L-25	118.3	12.7**	61.7	15.7**	1180	3.2	907	26.5*
Delcot 277/PSC355	130.0	11.4**	58.7	8.6*	1487	29.6**	768	4.8
DES 422/ Sphinx	115.0	0.0	57.3	-8.5**	1485	63.2**	618	-1.2
DES 422/ 94L-25	120.0	14.3**	53.0*	-0.6	1182	17.5	419	-41.6**
DES 422/PSC355	133.3	14.3**	66.3	7.5*	1198	4.5	1093	49.1**
DP90/Sphinx	113.3*	-1.4	53.7*	-13.4**	1637*	37.4**	767	8.7
DP90/ 94L-25	123.3	17.5**	56.3*	5.7	1398	17.3	903	26.0*
DP90/PSC355	125.0	7.1**	66.7	8.0**	1595	33.9**	888	21.2

Table 9. Continued.

Hybrid Combination	AWB PLTHT† (cm)	AWB Hb%‡	HYD PLTH (cm)	HYD Hb%	AWB YLD (kg ha^{-1})	AWB Hb%	HYD YLD (kg ha^{-1})	HYD Hb%
DP50/Sphinx	135.0	22.7**	55.7*	-1.8	1368	18.7	701	6.3
DP50/ 94L-25	126.7	20.6**	56.0*	15.1**	1354	17.5	872	21.7
DP50/PSC355	130.0	18.2**	53.0*	8.9*	1460	26.8**	593	-19.1
SC1/ Sphinx	118.3	2.9	56.3*	-0.6	1456	32.1**	611	-2.4
SC1/ 94L-25	120.0	14.3**	51.3*	-2.5	1344	21.9*	456	-36.4**
SC1/PSC355	120.0	4.3	57.0	8.2*	1544	34.7**	564	-23.0
PD6520/ Sphinx	116.7	1.4	54.3*	-4.2	1525	64.4**	548	-12.4
PD6520/ 94L-25	113.3*	7.9**	56.7	6.3	1214	20.7	744	3.7
PD6520/PSC355	136.7	17.1**	60.0	8.4*	1329	15.8	614	-16.2
CS8606/ Sphinx	116.7	12.9**	48.0*	-15.3**	1327	76.7**	306	-51.1**
CS8606/ 94L-25	116.7	12.9**	51.3*	3.4	1014	0.8	725	1.1
CS8606/PSC355	130.0	25.8**	49.0*	-1.3	1275	11.2	518	-29.3**
TAM 0155/Sphinx	100.0*	-13.0**	52.0*	-13.3**	1605*	35.0**	631	0.8
TAM 0155/ 94L-25	120.0	14.3**	58.3	9.4**	1349	13.5	842	17.4
TAM 0155/PSC355	133.3	14.3**	53.0*	-11.7**	1212	1.9	697	-4.9
TAM 73840/ Sphinx	108.3*	1.6	51.3*	-9.5**	1236	45.9**	663	5.9
TAM 73840/ 94L-25	108.3*	3.2	49.0*	-8.1*	1494	48.6**	714	-0.4
TAM 73840/PSC355	123.3	15.6**	63.3	15.9**	1140	-0.6	910	24.2**
LA 887/ Sphinx	121.7	5.8*	55.0*	-13.2**	1516	38.8**	752	-33.0**
LA 887/94L-25	128.3	22.2**	62.3	16.9**	923	-15.4	903	-19.5*
LA 887/PSC355	135.0	15.7**	57.7	-6.5*	1166	1.6	756	-32.6**
MD 51ne/ Sphinx	108.3*	-5.8*	58.3	-4.4	1560	20.2*	915	-10.6
MD 51ne/ 94L-25	133.3	27.0**	54.7*	2.6	1711*	31.8**	1042	1.8
MD 51ne/PSC355	138.3	18.5**	66.3	8.7**	1181	-9.1	899	-12.2
Ciano Alamos 92/ Sphinx	118.3	2.9	53.0*	-6.5	1847*	58.6**	720	15.0
Ciano Alamos 92/ 94L-25	116.7	11.1**	57.0	25.7**	1402	20.3*	787	9.7
Ciano Alamos 92/PSC355	130.0	11.4**	60.7	33.8**	1517	30.2**	583	-20.4
Ciano Cocorim 92/Sphinx	108.3*	-5.8*	55.0*	-3.0	1608*	29.6**	812	27.4
Ciano Cocorim 92/94L-25	118.3	12.7**	59.3	11.3**	1333	7.5	1094	52.6**
Ciano Cocorim 92/PSC355	121.7	5.8*	60.7	9.6**	1089	-12.2	929	26.7*
TAM 86 GGG-30/ Sphinx	113.3*	4.6	61.7	8.8**	1126	-27.0**	962	53.7**
TAM 86 GGG-30/94L-25	116.7	11.1**	64.7	30.2**	1099	-28.7**	1008	40.6**
TAM 86 GGG-30/PSC355	128.3	18.5**	64.3	29.5**	1081	-29.9**	961	31.1*

Table 9. Continued.

Hybrid Combination	AWB		HYD		AWB		HYD	
	PLTHT†	Hb%‡	PLTHT	Hb%	YLD	Hb%	YLD	Hb%
	(cm)		(cm)		(kg ha^{-1})		(kg ha^{-1})	
Acala Maxxa/ Sphinx	121.7	23.7**	56.3*	-0.6	1131	50.7**	580	-7.3
Acala Maxxa/94L-25	111.7*	13.6**	64.7	21.3**	946	-5.9	844	17.7
Acala Maxxa/PSC355	126.7	28.8**	64.0	18.5**	893	-22.2*	712	-2.9
CS8601/ Sphinx	111.7*	1.5	62.0	9.3**	1363	10.7	539	-13.9
CS8601/ 94L-25	115.0	9.5**	55.0*	5.1	1510	22.6*	628	-12.4
CS8601/PSC355	125.0	13.6**	52.3*	0.0	1364	10.8	606	-17.3
Acala 1517-99/ Sphinx	125.0	8.7**	59.7	-2.2	918	22.2	550	-12.1
Acala 1517-99/ 94L-25	128.3	22.2**	66.3	24.5**	858	-14.7	752	4.8
Acala 1517-99/PSC355	143.3	22.8**	61.7	1.1	755	-34.2**	679	-7.4
GA 161/ Sphinx	113.3*	-1.4	61.3	-2.6	1870*	134.9*	1079	32.6**
GA 161/ 94L-25	125.0	19.0**	62.0	16.3**	1201	19.4	980	20.4
GA 161/PSC355	128.3	10.0**	57.7	-6.5*	1273	11.0	636	-21.9*
TAM 88G-104/ Sphinx	121.7	9.0**	62.7	1.6	1906*	40.5**	889	-17.9*
TAM 88G-104/ 94L-25	120.0	14.3**	62.3	16.9**	1428	5.3	1116	3.1
TAM 88G-104/PSC355	128.3	14.9**	59.0	-4.3	1419	4.6	894	-17.4*
Tamcot 73/ Sphinx	120.0	7.5**	51.0*	-11.0**	1904*	32.0**	787	25.6
Tamcot 73/94L-25	113.3*	7.9**	52.0*	-2.4	1357	-5.8	1122	56.5**
Tamcot 73/PSC355	126.7	13.4**	61.7	7.6*	1491	3.4	1125	53.4**
All Tex 7A21/ Sphinx	123.3	7.2**	65.3	7.1*	1862*	52.0**	1101	75.8**
All Tex 7A21/ 94L-25	120.0	14.3**	63.3	18.8**	1314	7.3	926	29.2*
All Tex 7A21 /PSC355	136.7	17.1**	55.0*	-9.8**	1352	10.4	674	-8.1
UA48/ Sphinx	121.7	5.8*	55.0*	-6.3	1994*	13.9*	590	-56.0**
UA48/TAM 94L-25	111.7*	6.3*	52.0*	-2.4	1579	-9.8	973	-27.4**
UA48/PSC355	131.7	14.5**	63.3	8.0*	1461	-16.6*	988	-26.2**
Suraj (check)	130.0		66.0		1188		2059	

*Significant to Suraj at P=0.05 (For mean comparison with Suraj and heterosis different than zero)
** Significant to Suraj at P=0.01 (For mean comparison with Suraj and heterosis different than zero)
† PLTHT=Plant height (cm); YLD=Seed cotton yield kg ha^{-1}.
‡ Hb% = heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25, AWB=Aurangabad, HYD=Hyderabad

At AWB location, short to medium SL ranging between 28.0 mm and 32.9 mm were observed for the F_1 hybrids in this study (Table 10). Two genotypes GA 161/TAM94L-25 (32.9 mm) and UA48/TAM94L-25 (32.6 mm) outperformed Suraj (30.4 mm) in SL but the other 74 hybrids were not different than Suraj. Best parent heterosis for SL ranged from -10.7% to 5.6% with only Twelve hybrids having positive heterobeltiosis and nineteen hybrids having negative heterobeltiosis for SL.

Similar trends were observed at HYD for SL where these genotypes ranged between 26.7 mm to 33.2 mm with only one F_1 hybrid, UA48/TAM94L-25 (33.2 mm), outperforming Suraj (31.3 mm) while 36 other hybrids were not different than Suraj. The heterobeltiosis ranged from -9.1% to 6.8%, with 20 of the 33 genotypes exhibiting significant heterobeltiosis and were positive. UA48/TAM94L-25 exhibited a 3.5% heterobeltiosis. These data suggest that commercial hybrids developed for mechanical harvest in India could provide the additional advantage of heterosis for SL, depending on the specific combination, of course.

None of the 90 F_1 genotypes were found superior to Suraj for ELONG at AWB; ranging from 4.9 to 5.8 with Suraj averaging 5.5 (Table 10). A total of 54 hybrids had significant heterobeltiosis but only four hybrids had positive best parent heterosis. Similarly, at HYD, none of the 90 F_1 hybrids out performed Suraj (6.0) for ELONG with heterobeltiosis ranging from -9.0% to 4.5%. Again few hybrids exhibited positive and significant values with 10 having positive and significant and 67 having negative and significant high parent heterosis. These results are surprising and may indicate a complicating issue in developing F_1 hybrids for mechanical harvesting using US parental germplasm.

STR ranged between 190.7 to 249.8 kN m kg^{-1} for the 90 hybrids evaluated and only two hybrids Deltatype Webber/Tamcot Sphinx (249.8 kN m kg^{-1}) and Acala 1517-99/Tamcot Sphinx (248.4 kN m kg^{-1}) exhibited significantly superior STR compared to Suraj at 223.0 kN m kg^{-1} (Table 11). Eighty-one F_1 hybrid entries had STR not different than Suraj. Best parent heterosis ranged from -13.1% to 19.9% and 11 hybrids were significant and negative and 17 were significant and positive (17 F_1 hybrids) for STR heterobeltiosis over best parent. These data are encouraging in the sense that some hybrid combinations could result in heterosis for STR but not encouraging in the sense that more of these 90 F_1s did not exhibit heterosis for this important trait, suggesting few alleles for fiber HVI STR in elite, although obsolete, parental material.

MIC values were lower than expected in India with all but two F_1 hybrids, Rex/Tamcot Sphinx (3.7) and Ciano Almos 92/PSC355 (3.5), exhibiting MIC values within the US standard range of 3.5 to 4.9 (Table 11). Heterobeltiosis ranged from -28.1% to 13.7%, sixty five entries were found to have significantly negative best parent heterosis while only Rex/Tamcot Sphinx (13.7%) had positive significant heterobeltiosis. The Indian control cultivar, Suraj, also was well below the minimum global standard of 3.5 units. Interpretation of these data are suspect because MIC is known to be confounded in the sense that low MIC can be caused by fine fibers, i.e., fibers having a small perimeter but a mature secondary wall, or fibers that are immature with a large perimeter but a poorly developed secondary wall. It is likely that the low

MIC values in India in 2015 resulted from immature fibers caused by samples collected from mid to upper portion of plant which had less boll development period affecting secondary wall development. Secondly dense plant stand promotes vegetative growth, shedding of lower bolls and leaves which reduces the carbohydrates available to mature bolls.

Four F_1 hybrids had significantly superior UR compared with Suraj at 47.1. UR ranged from 45.9 to 48.8 (Table 11). Best parent heterosis was low with heterobeltiosis ranging from -6.6% to 3.5% with only one hybrid having positive and significant heterobeltiosis and 58 having negative and significant heterobeltiosis. These results are slightly problematic in that uniformity of fiber lengths is an important criterion to the spinner to prevent wastage.

Best parent heterosis described above for SL, MIC, UR and ELONG might indicate additive gene action which is discussed in detailed under GCA and SCA section. Karademir et al. (2011) and Ashokkumar et al. (2013) also reported varying degree of heterosis for fiber quality traits and the present study supports their findings.

Fiber quality traits MIC and UR showed overall negative heterosis with 65 and 58 hybrids, respectively, significantly inferior to best parent in terms of heterosis. Ashokkumar et al. (2013) also reported inferior MIC values in F_1 hybrids. This needs further study to find which factors are affecting these traits.

Overall wide heterosis range for YLD indicated that superior hybrid performance is expected from compact by compact cross combinations combining better SL and STR with careful selection for MIC and ELONG.

Parental line UA48 yielded well in India at 1545 kg ha^{-1} YLD which was equal to the in-country check, Suraj, at 1623 kg ha^{-1}. UA48 also exhibited significantly superior SL (32.7 mm) and MIC (3.2) while having comparable STR, UR and ELONG indicating it's desirable as a parent for varietal breeding as well. This observation is important in the sense that as the planting density increases, hybrid seed requirement also will rise and producing hybrid seed is tedious in cotton since the majority of hybrid seed is produced by hand emasculation and pollination method involving manual labor.

Table 10. Mean performance and heterobeltiosis based on best performing parent for 90 upland cotton hybrids for fiber properties grown at Aurangabad or Hyderabad, India, 2015.

Hybrid Combination	AWB		HYD		AWB		HYD	
	SL†	Hb%‡	SL	Hb%	ELONG	Hb%	ELONG	Hb%
	(mm)		(mm)		(%)		(%)	
Lone Star/ Sphinx	29.7	5.4**	30.3	3.7*	5.6	0.0	5.8	0.9
Lone Star/94L-25	29.5	-6.8**	31.0	4.8**	5.0	-2.0	5.5	-1.8*
Lone Star/PSC355	29.5	0.9	29.6	1.3	5.4	-4.5**	5.8	-5.7**
Deltatype Webber/Sphinx	29.7	5.2**	28.0	2.0	5.5	-1.8	5.5	-3.5**
Deltatype Webber/94L-25	30.1	-4.9**	30.1	1.7	5.2	2.0	5.8	3.6**
Deltatype Webber/PSC355	28.6	-1.9	29.0	2.5	5.2	-8.0**	5.9	-3.3**
Lightning Express/ Sphinx	28.5	1.1	28.6	4.8**	5.4	-4.5**	5.9	2.6**
Lightning Express/94L-25	29.7	-6.1**	29.9	1.1	5.1	-1.0	5.7	2.7**
Lightning Express/PSC355	30.4	4.1*	28.6	1.1	5.5	-2.7*	5.8	-5.7**
Mebane/Sphinx	28.1	-0.4	27.0	-1.2	5.4	-3.6**	5.5	-4.3**
Mebane/94L-25	28.2	-10.7**	29.7	0.2	5.2	1.0	5.7	-1.7*
Mebane/PSC355	28.3	-3.2	27.7	-2.2	5.3	-6.2**	5.8	-5.7**
Rex/Sphinx	29.4	4.4*	27.2	-0.4	5.5	-2.7*	5.6	-2.6**
Rex/94L-25	31.2	-1.2	29.8	0.5	5.2	2.0	5.6	-1.8*
Rex/PSC355	29.6	1.3	27.6	-2.5	5.6	-0.9	5.9	-4.1**
Auburn 56/Sphinx	28.9	-3.9*	28.1	1.3	5.4	-3.6**	5.6	-1.8*
Auburn 56/94L-25	30.5	-3.4	30.6	3.5*	5.1	-8.9**	5.8	4.5**
Auburn 56/PSC355	29.1	-3.2	29.1	2.9	5.6	-0.9	5.9	-4.1**
Stoneville 213/Sphinx	29.2	2.9	28.7	-2.9	5.4	-3.6**	5.9	3.5**
Stoneville 213/94L-25	30.0	-5.0**	29.4	-0.8	4.9	-4.9**	5.7	0.0
Stoneville 213/PSC355	29.2	0.1	27.5	-6.8**	5.1	-8.9**	5.6	-9.0**
DP16/ Sphinx	30.8	3.4	29.7	1.9	5.4	-3.6**	5.6	-1.8*
DP16/94L-25	31.6	0.1	30.8	3.9*	5.4	4.9**	5.7	0.0
DP16/PSC355	30.0	0.6	30.4	4.3*	5.6	-0.9	5.9	-4.1**
Delcot 277/ Sphinx	30.7	3.4	28.4	-2.3	5.5	-1.8	6.0	0.8
Delcot 277/94L-25	30.5	-3.5*	30.7	3.7*	5.3	-1.9	5.8	-1.7*
Delcot 277/PSC355	29.9	0.7	29.4	1.1	5.2	-8.0**	5.8	-4.9**
DES 422/ Sphinx	29.6	2.3	28.4	-1.2	5.5	-1.8	5.7	-0.9
DES 422/ 94L-25	30.6	-3.2	30.0	1.5	5.1	-7.3**	5.4	-3.6**
DES 422/PSC355	29.0	-0.6	30.6	6.2**	5.4	-4.5**	6.1	-0.8
DP90/Sphinx	29.5	2.0	29.4	-1.5	5.2	-8.0**	5.7	-0.9
DP90/ 94L-25	31.3	-0.9	30.2	1.0	5.4	0.9	5.6	-2.6**
DP90/PSC355	29.2	0.1	30.8	3.0	5.3	-5.4**	5.8	-4.9**

Table 10. Continued.

Hybrid Combination	AWB		HYD		AWB		HYD	
	SL†	Hb%‡	SL	Hb%	ELONG	Hb%	ELONG	Hb%
	(mm)		(mm)		(%)		(%)	
DP50/Sphinx	30.7	-1.7	27.5	-6.8**	5.3	-5.4**	5.5	-6.8**
DP50/ 94L-25	30.1	-4.9**	29.5	-0.3	5.2	-3.7**	5.6	-5.0**
DP50/PSC355	29.6	-5.0**	28.5	-3.6*	5.6	-0.9	6.0	-2.5**
SC1/ Sphinx	28.8	0.6	28.0	-1.6	5.5	-2.7*	5.6	-2.6**
SC1/ 94L-25	30.7	-2.8	29.6	-0.1	5.2	2.0	5.7	0.0
SC1/PSC355	28.0	-4.1*	27.8	-2.1	5.4	-4.5**	5.7	-7.4**
PD6520/ Sphinx	29.1	1.0	27.9	-0.3	5.3	-6.2**	5.6	-2.6**
PD6520/ 94L-25	31.3	-0.9	30.0	1.3	5.1	-1.0	5.6	-0.9
PD6520/PSC355	29.7	1.6	28.6	1.0	5.2	-8.0**	5.6	-9.0**
CS8606/ Sphinx	28.0	-0.6	26.7	-2.3	5.4	-4.5**	5.4	-5.3**
CS8606/ 94L-25	30.6	-3.2	29.6	-0.1	5.1	-1.0	5.7	2.7**
CS8606/PSC355	28.2	-3.5	27.0	-4.8**	5.2	-7.1**	5.6	-9.0**
TAM 0155/Sphinx	28.5	-0.8	28.6	4.7*	5.5	-1.8	5.6	-1.8*
TAM 0155/ 94L-25	30.2	-4.4*	30.6	3.2	5.3	1.0	5.7	3.6**
TAM 0155/PSC355	29.8	2.1	29.7	4.9**	5.4	-4.5**	5.7	-7.4**
TAM 73840/ Sphinx	30.1	5.6**	27.7	0.0	5.0	-10.7**	5.6	-2.6**
TAM 73840/ 94L-25	30.6	-3.2	27.7	-6.4**	5.3	2.9*	5.5	-5.2**
TAM 73840/PSC355	28.6	-2.1	28.5	0.7	5.2	-8.0**	5.7	-6.6**
LA 887/ Sphinx	28.7	-1.8	29.8	-2.9	5.6	-0.9	5.8	-2.5**
LA 887/94L-25	30.7	-2.7	30.4	-0.6	5.2	2.0	5.7	-5.0**
LA 887/PSC355	29.4	0.8	28.9	-5.7**	5.5	-1.8	5.9	-4.1**
MD 51ne/ Sphinx	30.3	5.5**	28.3	-4.1*	5.1	-9.8**	5.6	-5.1**
MD 51ne/ 94L-25	31.9	1.1	30.5	3.2	5.2	2.0	5.7	-4.2**
MD 51ne/PSC355	30.3	3.8*	29.0	-1.8	5.3	-5.4**	5.8	-4.9**
Ciano Alamos 92/ Sphinx	30.2	-2.6	27.6	-3.0	5.6	0.0	5.4	-6.1**
Ciano Alamos 92/ 94L-25	31.0	-2.0	30.0	1.5	5.1	-6.5**	5.6	0.0
Ciano Alamos 92/PSC355	30.2	-2.5	28.8	1.4	5.4	-3.6**	5.7	-6.6**
Ciano Cocorim 92/ Sphinx	29.0	0.6	28.0	-1.2	5.5	-1.8	5.6	-1.8*
Ciano Cocorim 92/94L-25	30.2	-4.3*	30.0	1.5	5.4	-1.8	5.7	1.8*
Ciano Cocorim 92/PSC355	29.6	1.4	29.4	3.5*	5.4	-3.6**	5.8	-4.9**
TAM 86 GGG-30/ Sphinx	29.4	4.3*	29.2	6.8**	5.4	-3.6**	5.8	0.9
TAM 86 GGG-30/94L-25	32.0	1.2	31.2	5.3**	5.3	-0.9	5.8	1.8*
TAM 86 GGG-30/PSC355	30.8	5.6**	29.5	4.1*	5.5	-2.7*	6.1	-0.8

Table 10. Continued.

Hybrid Combination	AWB		HYD		AWB		HYD	
	SL†	Hb%‡	SL	Hb%	ELONG	Hb%	ELONG	Hb%
	(mm)		(mm)		(%)		(%)	
Acala Maxxa/ Sphinx	30.6	-1.4	29.8	-3.3*	5.6	-0.9	5.7	-1.7*
Acala Maxxa/94L-25	30.2	-4.5*	31.3	1.4	5.3	-0.9	5.6	-3.4**
Acala Maxxa/PSC355	29.2	-5.9**	30.5	-1.2	5.6	-0.9	6.0	-2.5**
CS8601/ Sphinx	28.0	-0.8	28.1	-0.8	5.2	-8.0**	5.6	-2.6**
CS8601/ 94L-25	29.7	-5.9**	31.0	4.8**	5.0	-2.9*	5.7	2.7**
CS8601/PSC355	28.5	-2.3	29.5	4.2*	5.4	-3.6**	5.6	-8.2**
Acala 1517-99/ Sphinx	29.8	5.0*	28.4	-1.1	5.7	1.8	5.5	-4.3**
Acala 1517-99/ 94L-25	29.8	-5.6**	28.4	-4.0*	5.2	1.0	5.7	-1.7*
Acala 1517-99/PSC355	29.2	0.0	29.1	1.4	5.2	-7.1**	5.9	-3.3**
GA 161/ Sphinx	30.1	-0.4	28.9	-4.6**	5.6	-3.5**	5.7	-7.4**
GA 161/ 94L-25	32.9*	4.0*	32.0	5.7**	5.5	-5.2**	5.9	-4.1**
GA 161/PSC355	30.9	2.1	30.0	-0.9	5.6	-2.6*	5.8	-5.7**
TAM 88G-104/ Sphinx	30.2	4.9*	27.8	-0.8	5.6	-0.9	5.7	-1.7*
TAM 88G-104/ 94L-25	31.1	-1.6	30.8	4.0*	5.4	3.9**	5.6	-2.3**
TAM 88G-104/PSC355	29.2	0.0	29.4	3.7*	5.2	-7.1**	5.8	-4.9**
Tamcot 73/ Sphinx	30.9	2.2	29.9	-1.8	5.6	-2.6*	5.9	-4.1**
Tamcot 73/94L-25	31.6	0.1	30.8	1.1	5.5	-4.3**	5.7	-7.4**
Tamcot 73/PSC355	29.3	-3.0	30.0	-1.3	5.5	-4.3**	5.8	-4.9**
All Tex 7A21/ Sphinx	29.4	0.6	28.9	-1.0	5.5	-1.8	5.8	-1.7*
All Tex 7A21/ 94L-25	30.4	-3.9*	31.4	5.9**	5.3	-4.5**	5.9	0.0
All Tex 7A21 /PSC355	29.4	0.7	29.4	0.5	5.4	-3.6**	6.0	-1.6*
UA48/ Sphinx	30.9	-7.1**	29.2	-9.1**	5.8	3.6**	5.7	-4.2**
UA48/TAM 94L-25	32.6*	-2.2	33.2*	3.2*	5.4	-1.8	5.7	-3.4**
UA48/PSC355	30.9	-7.1**	31.1	-3.3*	5.5	-2.7*	5.7	-6.6**
Suraj (check)	30.4		31.3		5.5		6.0	

*Significant to Suraj at P=0.05 (For mean comparison with Suraj and heterosis different than zero)
** Significant to Suraj at P=0.01 (For mean comparison with Suraj and heterosis different than zero)
† SL=Fiber length in mm; ELONG=Fiber elongation.
‡ Hb% i.e. heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25, AWB=Aurangabad, HYD=Hyderabad

Table 11. Mean performance and heterobeltiosis based on best performing parent for 90 upland cotton hybrids for fiber properties. Means averaged over Aurangabad and Hyderabad, India, 2015.

Hybrid Combination	STR†	Hb%‡	MIC	Hb%	UR	Hb%
	(kN m kg^{-1})		(Unit)		(Ratio)	
Lone Star/ Sphinx	234.6	13.3**	2.7	-17.0**	46.6	-3.7**
Lone Star/94L-25	205.1	-1.5	2.6	-13.3**	46.7	3.5**
Lone Star/PSC355	201.6	-3.9	2.6	-19.9**	47.1	-2.8**
Deltatype Webber/Sphinx	249.8*	18.1**	2.9	-11.9**	47.0	-4.2**
Deltatype Webber/94L-25	211.6	0.1	2.7	-11.2**	46.7	-4.8**
Deltatype Webber/PSC355	205.5	-2.8	2.5	-25.0**	47.6	-3.0**
Lightning Express/ Sphinx	224.7	8.5*	2.8	-14.7**	47.5	-4.5**
Lightning Express/94L-25	193.9	-6.9*	2.5	-17.8**	47.1	-5.4**
Lightning Express/PSC355	214.3	2.2	3.3*	-0.9	47.5	-4.6**
Mebane/Sphinx	213.9	3.2	2.9	-10.6**	48.8*	-3.2**
Mebane/94L-25	211.1	1.4	2.6	-12.0**	47.4	-5.9**
Mebane/PSC355	202.2	-3.6	3.0	-10.6**	47.9	-5.1**
Rex/Sphinx	210.8	1.7	3.7*	13.7**	47.6	-1.6
Rex/94L-25	203.6	-2.2	3.0	1.1	46.8	-1.8
Rex/PSC 355	205.7	-1.9	3.2*	-4.3	48.2*	-0.3
Auburn 56/Sphinx	216.6	-4.4	2.8	-12.4**	47.5	-1.8
Auburn 56/94L-25	209.9	-7.4*	2.6	-15.0**	46.8	0.0
Auburn 56/PSC355	217.7	-4.0	2.8	-15.4**	47.1	-2.5*
Stoneville 213/Sphinx	202.2	-2.4	3.1*	-3.6	48.1*	-0.6
Stoneville 213/94L-25	194.9	-6.4	2.7	-10.3**	46.7	-0.3
Stoneville 213/PSC355	202.9	-3.2	2.6	-20.7**	46.9	-2.9**
DP16/ Sphinx	224.0	8.2*	2.7	-17.0**	46.3	-4.4**
DP16/94L-25	215.3	3.4	3.1	2.8	46.5	-0.7
DP16/PSC355	225.1	7.4*	2.8	-14.4**	46.8	-3.1**
Delcot 277/ Sphinx	204.8	-1.1	3.3*	3.1	47.5	-1.8
Delcot 277/94L-25	206.8	-0.7	3.0	-0.7	46.6	-0.7
Delcot 277/PSC355	205.7	-1.9	2.8	-15.9**	46.4	-4.0**
DES 422/ Sphinx	238.5	-0.3	2.8	-12.1**	47.6	-1.7
DES 422/ 94L-25	208.0	-13.1**	2.8	-5.8	47.1	-0.2
DES 422/PSC355	210.1	-12.2**	2.8	-16.1**	46.5	-3.7**
DP90/Sphinx	206.8	-3.5	2.5	-23.5**	47.3	-2.2*
DP90/ 94L-25	228.2	6.4*	2.7	-15.2**	46.5	-1.9
DP90/PSC355	230.7	7.6*	3.0	-10.6**	47.0	-2.6**

Table 11. Continued.

Hybrid Combination	STR	Hb%	MIC	Hb%	UR	Hb%
	(kN m kg-1)		(Unit)		(Ratio)	
DP50/Sphinx	220.4	6.4	2.8	-14.9**	47.4	-2.1*
DP50/ 94L-25	195.3	-6.2	2.7	-8.8**	46.8	-0.2
DP50/PSC355	214.6	2.4	2.8	-15.7**	47.3	-2.0*
SC1/ Sphinx	215.8	2.4	2.9	-10.3**	47.9	-1.0
SC1/ 94L-25	215.7	2.4	2.8	-6.9	46.7	-0.7
SC1/PSC355	210.9	0.1	2.7	-17.2**	47.6	-1.4
PD6520/ Sphinx	196.6	-5.1	2.8	-14.7**	47.5	-1.9
PD6520/ 94L-25	208.0	-0.1	2.9	-3.6	46.3	-2.3*
PD6520/PSC355	203.8	-2.8	3.1*	-4.8	46.9	-2.9**
CS8606/ Sphinx	200.8	-3.1	3.0	-8.1*	48.4*	-2.7**
CS8606/ 94L-25	197.8	-5.0	2.6	-12.2**	46.4	-6.6**
CS8606/PSC355	209.4	-0.1	2.8	-16.7**	47.1	-5.2**
TAM 0155/Sphinx	230.9	11.5**	3.0	-7.0	47.5	-2.3*
TAM 0155/ 94L-25	210.0	0.8	2.6	-12.5**	46.5	-4.2**
TAM 0155/PSC355	200.5	-4.4	2.8	-16.2**	47.0	-3.2**
TAM 73840/ Sphinx	190.7	-8.0*	2.9	-20.6**	47.6	-2.0*
TAM 73840/ 94L-25	219.9	5.6	2.9	-19.3**	47.6	-2.0*
TAM 73840/PSC355	195.4	-6.8*	2.6	-28.1**	48.0	-1.2
LA 887/ Sphinx	230.6	5.4	2.7	-15.9**	46.9	-3.1**
LA 887/94L-25	217.7	-0.5	2.8	-6.1	46.2	-2.1*
LA 887/PSC355	216.5	-1.0	2.6	-20.1**	47.3	-2.1*
MD 51ne/ Sphinx	221.9	7.1*	2.7	-16.0**	46.9	-3.2**
MD 51ne/ 94L-25	230.1	10.5**	2.9	-3.3	46.5	-1.9
MD 51ne/PSC355	205.8	-1.8	2.8	-13.8**	46.4	-4.0**
Ciano Alamos 92/ Sphinx	209.9	-5.9	3.2*	0.0	47.5	-1.8
Ciano Alamos 92/ 94L-25	201.0	-9.9**	3.1	2.2	46.5	-2.4*
Ciano Alamos 92/PSC355	204.6	-8.3**	3.5*	5.6	47.0	-2.7**
Ciano Cocorim 92/Sphinx	199.2	-12.2**	3.0	-7.1	47.6	-1.6
Ciano Cocorim 92/94L-25	210.3	-7.3*	2.8	-7.8**	46.8	-1.1
Ciano Cocorim 92/PSC355	214.8	-5.4	2.7	-18.4**	46.5	-3.6**
TAM 86 GGG-30/ Sphinx	220.0	1.3	2.8	-13.2**	46.7	-4.5**
TAM 86 GGG-30/94L-25	218.1	0.4	2.7	-16.3**	46.0	-6.0**
TAM 86 GGG-30/PSC355	208.6	-3.9	2.6	-21.5**	46.9	-4.1**

Table 11. Continued.

Hybrid Combination	STR (kN m kg-1)	Hb%	MIC (Unit)	Hb%	UR (Ratio)	Hb%
Acala Maxxa/ Sphinx	246.1	9.6**	2.7	-16.5**	47.2	-2.6**
Acala Maxxa/94L-25	223.4	-0.5	3.1*	4.4	47.1	0.1
Acala Maxxa/PSC355	216.7	-3.5	2.8	-16.7**	46.9	-2.9**
CS8601/ Sphinx	218.1	5.3	2.9	-11.6**	47.8	-1.3
CS8601/ 94L-25	203.6	-2.2	2.9	-9.9**	46.3	-3.5**
CS8601/PSC355	211.4	0.8	2.8	-15.6**	47.7	-1.3
Acala 1517-99/ Sphinx	248.4*	19.9**	2.8	-12.1**	47.5	-2.9**
Acala 1517-99/ 94L-25	235.8	13.2**	2.6	-12.2**	47.2	-3.4**
Acala 1517-99/PSC355	209.2	-0.2	2.7	-18.8**	46.9	-3.9**
GA 161/ Sphinx	220.6	-4.5	3.2*	0.1	47.3	-2.3*
GA 161/ 94L-25	217.0	-6.0*	2.7	-13.9**	46.1	-2.1*
GA 161/PSC355	222.7	-3.5	2.8	-13.9**	46.7	-3.3**
TAM 88G-104/ Sphinx	230.3	11.2**	2.9	-9.3*	47.7	-1.4
TAM 88G-104/ 94L-25	214.7	3.1	3.0	0.7	45.9	-4.2**
TAM 88G-104/PSC355	208.5	-0.6	2.8	-15.4**	46.8	-3.2**
Tamcot 73/ Sphinx	229.3	6.0	3.0	-8.0*	46.9	-3.0**
Tamcot 73/94L-25	231.0	6.8*	2.8	-9.8**	46.5	-0.9
Tamcot 73/PSC355	211.5	-2.3	3.0	-8.8*	46.8	-3.0**
All Tex 7A21/ Sphinx	216.3	-0.2	2.8	-12.9**	47.9	-1.0
All Tex 7A21/ 94L-25	227.9	5.2	2.8	-5.3	46.9	-1.2
All Tex 7A21 /PSC355	222.8	2.8	2.7	-18.3**	46.9	-2.8**
UA48/ Sphinx	246.7	13.1**	3.3*	1.8	46.9	-3.1**
UA48/TAM 94L-25	233.5	7.0*	3.1*	-1.6	46.2	-0.7
UA48/PSC355	207.4	-4.9	2.9	-11.9**	46.1	-4.5**
Suraj	223.0		2.8		47.1	

*Significant to Suraj at P=0.05 (For mean comparison with Suraj and heterosis different than zero)
** Significant to Suraj at P=0.01 (For mean comparison with Suraj and heterosis different than zero)
† STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio.
‡ Hb% = heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25

Line x tester ANOVA, GCA and SCA analysis – India

The combined analysis across locations revealed significant differences among genotypes for all traits measured except OVCNT and SDCNT (Table 12). A significant Genotype x Location interaction was also found for all traits except GINOT, SDINX, STR, MIC and UR. This significant interaction suggested that entries differed in their performance for those traits at the two locations in India. Ouyang et al. (1995) described four patterns of genotype by environment interactions. Pattern 1 is no interaction, pattern 2 is interaction but no crossover, pattern 3 is interaction with equal shifts, and pattern 4 is crossover but unequal shifts. Under the present study, non-crossover type of Genotype x Location interactions were observed for YLD and PLTHT where mean performance for all entries at the AWB location was higher than the HYD location (data not shown). Crossover type of interaction was present for BOLWT (3 entries) and ELONG (4 entries) with higher mean performance at the HYD location. The SL Genotype x Location interaction was a crossover interaction where many entries differed in their performance indicating SL is highly affected by location (data not presented).

The variation due to genotypes was further segregated into parents, hybrids and parent vs hybrids (Table 12). Parents were significantly different for all the traits, as expected, and the same was observed for hybrids except for OVCNT. The significant variation among parents was more due to lines being significantly different for all the traits. This finding was not unexpected as the lines represent an array of obsolete US cultivars, some near modern and non-transgenic cultivars, and some unique germplasms released by Texas A&M AgriLife Research. Testers, on the other hand, were non-significant for traits except BOLWT, GINOT, SDINX, SL, UR and ELONG. The parent vs hybrids comparison with a single degree of freedom, which indicates average degree of heterosis, was also significant for all the traits except OVCNT.

The variation due to hybrids was further partitioned into variation due to lines in a hybrid combination (line (hybrid)), due to tester (tester (hybrid)) and the interaction effect of line by tester (LXT (hybrid)). Many authors have interpreted underlying gene action for the trait by comparing the mean squares due to the LXT (hybrid) to the mean squares of lines (hybrid) and tester (hybrid). While there are no absolute thresholds or statistical analysis, a greater mean square value for LXT (hybrid) relative to the mean square for lines and/or testers suggests a larger contribution from dominance gene action and lower contribution from additive gene action.

Table 12. Mean squares from line x tester analysis for 90 F_1 upland cotton hybrids and parental lines for indicated traits across two locations Aurangabad and Hyderabad, India 2015.

S.O.V	df	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX
Location (Loc)	1	1031.0*	1083.7**	499728908**	203.7**	729511.1**	1.9	1.6
Rep(Loc)	4	53.0	14.4	260138	6.3	159.0	5.7	15.9
Genotypes (Gen)	122	4.8	8.6	327211**	1.3**	193.5**	16.5**	4.1**
Parents	32	8.1**	7.9**	436456**	1.5**	232.0**	26.5**	4.6**
Lines	29	8.5**	8.1**	464913**	1.5**	239.4**	25.2**	4.4**
Testers	2	6.5	7.7	99129	1.7**	155.6	21.2**	4.2*
Parent Vs Hybrids	1	1.1	84.5**	9533555**	32.5**	1053.9**	10.8*	11.8**
Hybrids	89	3.6	8.0**	184490**	0.8**	170.0**	13.0**	3.9**
Line (hybrid)	29	5.9**	10.1**	409490**	0.8**	178.4**	21.8**	5.5**
Tester(hybrid)	2	4.8	8.2	372815**	12.1**	2725.3**	86.4**	38.0**
LXT(hybrid)	60	2.5	7.0**	65502	0.4*	78.03	6.02**	1.8**
Gen*Loc	122	4.6**	7.3**	149113**	0.6**	98.7**	0.3	0.1
Parents*Loc	32	4.7*	10.9**	119163**	0.6**	67.9	0.3	0.1
Hybrids*Loc	89	4.4**	6.1**	150790**	0.6**	103.4**	0.3	0.1
Error	488	2.9	4.1	54277	0.3	67.2	2.0	1.1
CV (%)		5.22	6.66	24.02	12.49	9.14	3.57	10.98

*Significant at P=0.05

** Significant at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g);

Table 12. Continued.

S.O.V	df	SL†	STR	MIC	UR	ELONG
Location (Loc)	1	48.1	4850.2	4.8	4.9	19.4
Rep(Loc)	4	21.3	46459.1**	7.8	86.0	2.4
Genotypes (Gen)	122	8.9**	1123.1**	0.3**	3.7**	0.1**
Parents	32	13.1**	1284.9**	0.4**	6.4**	0.2**
Lines	29	13.5**	1417.2**	0.3**	6.3**	0.2**
Testers	2	12.6**	9.7	0.1	10.2**	0.3**
Parent Vs Hybrids	1	112.4**	7427.4**	1.0**	76.2**	0.2*
Hybrids	89	6.2**	994.1**	0.3**	1.9**	0.1**
Line (hybrid)	29	8.6**	1318.9**	0.4**	2.3**	0.1**
Tester(hybrid)	2	114.2**	4898.2**	0.6**	26.4**	0.7**
LXT(hybrid)	60	1.2	697.1*	0.2**	0.8	0.04
Gen*Loc	122	1.9**	177.8	0.04	1.1	0.1**
Parents*Loc	32	2.4**	133.1	0.1	1.3	0.06*
Hybrids*Loc	89	1.6*	194.7	0.1	0.9	0.04
Error	488	1.2	471.6	0.1	1.0	0.04
CV (%)		3.72	10.19	10.28	2.09	3.49

*Significant at P=0.05

** Significant at P=0.01

† SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

Table 13. Percent contribution of lines, testers and line x tester interaction to variation among hybrids at India locations, 2015.

S.O.V	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
Lines	52.6	41.0	72.3	31.8	34.2	54.7	46.8	45.6	43.3	48.8	38.9	41.7
Testers	2.9	2.3	4.3	33.2	36.0	17	20.3	39.69	11.0	4.6	30.5	21.7
Line x Tester	46.1	58.2	27.2	34.0	29.9	30.3	31.1	13.37	45.7	46.8	29.2	35.7

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g); SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

In the current study involving the Indian locations, variance due to LXT (hybrids) source was less than the variance of lines (hybrid) and testers (hybrid) for all traits indicating a predominance of additive gene action over non additive (Table 12). Generally, these results are in agreement with earlier reports (Ragsdale, 2003; Wajid et al., 2011; Samreen et al., 2008). A higher percent of the total variance was attributable to lines than testers or LXT for OVCNT, YLD, GINOT, SDINX, SL, MIC, UR and ELONG (Table 13). For PLTHT, the tester contribution was greater. Higher contribution from interaction term for traits like SDCNT, BOLWT and STR suggest that specific combinations of parents will be superior to other hybrid combinations. For example, hybrid combinations with Deltatype Webber/Tamcot Sphinx and Acala 1517-99/Tamcot Sphinx exhibited superior for STR of 249.8 kN m kg^{-1} and 248.4 kN m kg^{-1} and heterosis of 18.1% and 19.9 %, respectively, as compared with the remaining F_1 hybrids (Table 11).

Breeders often are interested in the GCA of parental lines since such information indicates the “breeding value” of particular lines, which helps them decide which lines to use as parents in crosses to improve a trait of interest. Similarly, SCA helps identify superior combinations that might lie outside of expectations when planning breeding strategies. Furthermore, GCA and SCA estimates also indicate the underlying gene action for a specific trait enabling breeders to adopt suitable breeding strategies. GCA consists of additive and additive epistatic variance while SCA is dominance and all types of non-additive epistatic variances.

In the present study, GCA and SCA effects were calculated to understand the best combining genotype(s) for particular traits and to identify specific F_1 combinations that have significant SCA. GCA effects were calculated for lines and testers as deviation from grand overall mean (difference between the mean of all hybrid combinations based on a particular line and the grand overall mean) and their significance was tested by calculating standard error of difference and 't' values. SCA effects were calculated by subtracting the GCA effect of the line and tester involved in the hybrid combination and overall mean from the mean of specific hybrid combination.

The GCA effects for lines combined over the two Indian locations are presented in Table 14. Five lines revealed significant GCA effects for OVCNT. CS8606 (0.91) had highest positive GCA effect while PD6520 (-2.08) exhibited highest negative GCA effect when crossed with the three testers in this study and grown at two locations in India. Four lines, namely Lone Star (1.26), Mebane (1.03), TAM 0155 (0.83) and TAM88G-104 (0.79) had positive and significant GCA effects for SDCNT while Lightning express (-1.69) and PD6520 (-2.42) were the poorest combiners for this trait. Mebane was only genotype which had positive significant GCA for both OVCNT and SDCNT.

For YLD, six lines, Lone Star (-257.0 kg ha^{-1}), Deltatype Webber (-310.8 kg ha^{-1}), Mebane (-152.7 kg ha^{-1}), CS8606 (-177.6 kg ha^{-1}), Acala Maxxa (-187.3 kg ha^{-1}), and Acala 1517-99 (-286.6 kg ha^{-1}), had negative and significant GCA while Tamcot 73 (259.1 kg ha^{-1}), UA48 (225.8 kg ha^{-1}), TAM88G-104 (236.6 kg ha^{-1}), All Tex 7A21 (166.4 kg ha^{-1}), MD51 ne (179.6 kg ha^{-1}), GA 161 (134.9 kg ha^{-1}), DP90 (159.7 kg ha^{-1}), Ciano Cocorim 92 (105.8 kg ha^{-1}) and Ciano Almos 92 (104.2 kg ha^{-1}) were positive combiners with the testers studied (Table 14).

Acala 1517-99 (-0.47 g), SC1 (-0.30 g), Lightning Express (-0.37 g), DES 422 (-0.26 g) and DP50 (-0.22 g) were negatively significant for BOLWT while TAM 0155 (0.30 g), Acala Maxxa (0.30 g), Lone Star (0.23 g), Ciano Cocorim 92 (0.23g) and TAM 86 GGG-30 (0.28 g) had significant and positive GCA for BOLWT (Table 14).

Significant and positive GCA for PLTHT was observed for five parental lines namely Lone Star, Lightning Express, Stoneville 213, Acala 1517-99 and All Tex 7A21 which is not desirable to breed short plant types. However, TAM 73840 (-6.41 cm), CS8606 (-5.07 cm), SC1 (-3.18 cm), TAM 0155 (-4.24 cm) and CS8601 (-3.52 cm) combined with the testers in this study for reduced PLTHT. However, CS8606 also had negative GCA for YLD.

Nine and eight lines exhibited positive and negative significant GCA, respectively, for GINOT with All Tex 7A21 (2.37%) and TAM86GGG-30 (-3.10%) exhibiting the highest positive and negative effect, respectively, for GINOT. For SDINX, eight and six lines were positively and negatively significant, respectively. Correlation analysis revealed a significant negative relationship between SDINX and GINOT (r =0.39). No single line in this study was identified as the optimum parent in hybrid combination with the testers in the study for agronomic and boll properties.

Positive and highly significant GCA effects for SL were noted for UA48 (1.72 mm), GA 161 (1.16 mm), DP16 (0.93 mm), Tamcot 73 (0.81 mm), Acala Maxxa (0.64 mm), TAM86GGG-30 (0.72 mm), and MD 51ne (0.46 mm) (Table 14). Highly significant and negative GCA effects for SL were observed for Mebane (-1.46 mm), CS8606 (-1.28 mm), SC1 (-0.80 mm), TAM 73840 (-0.75 mm) and Stoneville 213 (-0.60 mm), while CS8601 (-0.47 mm), Acala 1517 (-0.48 mm), Rex (-0.48 mm) were significantly negative. STR GCA effects ranged between -14.8kN m kg^{-1} (Stoneville 213) to 16.3 kN m kg^{-1} (Acala 1517-99). UA48 (14.4 kN m kg^{-1}), Acala Maxxa (13.9 kN m kg^{-1}) and Tamcot 73 (9.1 kN m kg^{-1}) also exhibited positive and significant GCA for STR. MIC GCA was positively significant for four lines, Rex (0.44), Ciano Almos 92 (0.41), UA48 (0.26) and Delcot 277 (0.18). However, breeders must keep in mind that MIC is neither maximized nor minimized in breeding programs. Three and four lines had positive or negative and significant GCA, respectively, for UR, while six lines expressed negative and significant GCA effects for ELONG and six expressed positive GCAs.

Based on the GCA effects of these lines in hybrid combination with the three testers when grown in India, Tamcot 73 and UA48 offer the most promise for producing improved hybrids for production. Both combined with the testers to significantly improve YLD, SL, STR, and ELONG (Table 14). However, UA48 significantly reduced OVCNT and UR. Both tended to reduce PLTHT.

Table 14. GCA effects of lines from line x tester analysis in upland cotton across Aurangabad and Hyderabad, India, 2015.

Genotype	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
	(No)	(No)	(kg ha^{-1})	(g)	(cm)	(%)	(g)	(mm)	(kN m kg^{-1})	(Unit)	(Ratio)	(%)
Lone Star	0.61	1.26**	-257.0**	0.23*	3.93*	0.79**	-1.03**	0.31	-1.1	-0.21**	-0.23	-0.02
Deltatype Webber	0.39	0.33	-310.8**	-0.19	0.43	-1.89**	0.89**	-0.36	7.5	-0.19**	0.06	-0.01
Lightning Express	-0.66*	-1.69**	68.4	-0.37**	5.71**	-0.76**	-1.06**	-0.32	-3.8	-0.02	0.33	0.02
Mebane	0.88*	1.03*	-152.7**	-0.04	-1.18	0.30	-0.36	-1.46**	-5.8	-0.02	1.00**	-0.06
Rex	0.00	-0.09	9.5	0.17	-2.35	-0.78**	0.69**	-0.48*	-8.1	0.44**	0.46*	0.02
Auburn 56	0.33	0.45	-37.3	0.05	0.37	-1.49**	-0.22	-0.20	-0.1	-0.13*	0.09	0.04
Stoneville 213	0.05	-0.49	-50.0	-0.15	3.15*	1.03**	0.03	-0.60**	-14.8**	-0.04	0.21	-0.09*
DP16	-0.09	-0.71	-44.5	0.06	-0.85	-1.06**	0.50*	0.93**	6.7	0.01	-0.52*	0.07
Delcot 277	-0.3	-0.33	52.5	0.16	-0.96	-0.83**	0.53*	0.31	-9.1*	0.18**	-0.22	0.07
DES 422	-0.42	0.26	-39.0	-0.26*	0.48	1.20**	-0.69**	0.11	4.0	-0.04	0.02	-0.01
DP90	-0.47	0.14	159.7**	0.14	-0.63	-0.07	-0.61**	0.47*	7.1	-0.16*	-0.1	-0.04
DP50	-0.35	0.35	19.5	-0.22*	2.37	-0.81**	-0.31	-0.30	-4.7	-0.09	0.13	-0.02
SC1	0.11	-0.55	-71.2	-0.30**	-3.18*	1.12**	0.11	-0.80**	-0.7	-0.04	0.37	-0.03
PD6520	-2.08**	-2.42**	-42.6	-0.17	-0.74	0.11	0.39	-0.20	-12.0**	0.08	-0.15	-0.15**
CS8606	0.91*	-0.26	-177.6**	-0.12	-5.07**	0.29	0.28	-1.28**	-12.2**	-0.07	0.27	-0.14**
SE (lines)	0.39	0.47	53.9	0.12	1.90	0.32	0.23	0.25	5.03	0.06	0.22	0.07

Table 14. Continued.

Genotype	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
	(No)	(No)	(kg ha^{-1})	(g)	(cm)	(%)	(g)	(mm)	(kN m kg^{-1})	(Unit)	(Ratio)	(%)
TAM 0155	0.24	0.83*	17.6	0.30**	-4.24*	0.06	0.94**	-0.06	-1.1	-0.05	-0.06	0.01
TAM 73840	0.61	0.34	-12.2	0.2	-6.41**	-0.42	0.97**	-0.75**	-12.8**	-0.07	0.68**	-0.15**
LA 887	0.35	0.31	-35.6	0.03	2.98	0.98**	-0.39	0.04	6.8	-0.13*	-0.25	0.08*
MD 51ne	0.12	0.38	179.6**	0.11	2.87	0.22	-0.17	0.46*	4.5	-0.03	-0.47*	-0.08*
Ciano Alamos 92	-0.19	-0.55	104.2*	0.14	-1.07	0.37	-0.06	0.02	-9.7*	0.41**	-0.02	-0.07
Ciano Cocorim 92	-0.39	0.78	105.8*	0.23*	-3.13	0.32	0.47*	-0.24	-6.8	-0.01	-0.04	0.04
TAM 86 GGG-30	-0.19	0.00	1.2	0.28*	1.15	-3.10**	0.25	0.72**	0.7	-0.13*	-0.47*	0.12**
Acala Maxxa	0.02	0.40	-187.3**	0.30**	0.48	1.27**	-0.31	0.64**	13.9**	0.01	0.00	0.09*
CS8601	-0.06	-0.09	-36.6	-0.20	-3.52*	-0.43	-0.42*	-0.47*	-3.8	-0.02	0.20	-0.12**
Acala 1517-99	-0.21	0.25	-286.6**	-0.47**	7.04**	1.14**	-0.39	-0.48*	16.3**	-0.13*	0.17	0.01
GA 161	0.21	0.21	134.9**	0.08	0.93	-0.35	0.67**	1.16**	5.3	0.08	-0.36	0.13**
TAM 88G-104	0.19	0.79*	236.6**	0.14	1.98	0.93**	0.00	0.12	3.0	0.09	-0.24	0.02
Tamcot 73	0.13	0.14	259.1**	-0.06	-2.91	0.25	-0.31	0.81**	9.1*	0.09	-0.27	0.14**
All Tex 7A21	-0.54	-0.49	166.4**	-0.11	3.59*	2.37**	-0.50*	0.19	7.5	-0.07	0.20	0.12**
UA48	0.79*	-0.38	225.8**	0.11	-1.13	-0.49	0.28	1.72**	14.4**	0.26**	-0.64**	0.10*
SE (lines)	0.39	0.47	53.9	0.12	1.90	0.32	0.23	0.25	5.03	0.06	0.22	0.07

*Significantly different than zero at P=0.05

** Significantly different than zero at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index(g). SL=Fiber length (mm); STR=Fiber strength (kN m kg^{-1}); MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation.

Table 15. GCA effects of testers from line x tester analysis in upland cotton across Aurangabad and Hyderabad, India, 2015.

Genotype	OVCNT†	SDCNT	YLD	BOLWT	PLTHT	GINOT	SDINX	SL	STR	MIC	UR	ELONG
	(No)	(No)	(kg ha^{-1})	(g)	(cm)	(%)	(g)	(mm)	(kN m kg^{-1})	(Unit)	(Ratio)	(%)
Tamcot Sphinx	-0.12	0.05	51.54	-0.04	-3.03	0.45	-0.24	-0.60**	5.81	0.07	0.39*	0.02
TAM 94L-25	0.19*	0.20	-15.10	0.28*	-1.38	-0.80**	0.53*	0.90**	-1.5	-0.04	-0.40*	-0.08*
PSC355	-0.07	-0.22	-36.04	-0.25*	4.40*	0.34	-0.29	-0.30	-4.28	-0.03	0.01	0.06
SE (tester)	0.10	0.47	53.98	0.12	1.90	0.32	0.23	0.25	5.03	0.06	0.22	0.04

*Significantly different than zero at P=0.05
** Significantly different than zero at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; BOLWT=Boll weight (g); PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g); SL=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR=Fiber uniformity ratio; ELONG=Fiber elongation

At least one tester differed significantly from zero for GCA effects for all traits except SDCNT, YLD, STR and MIC (Table 15). This validates the selection of testers for the experiment. Tamcot Sphinx appears to be the best overall or general tester when used with the lines in this study and exhibited positive, but not significant, GCA for YLD. However, its hybrids with the lines in this study averaged 0.6 mm below the average SL for all combinations. As expected, TAM94L-25 exhibited highly significant and positive GCA for SL (0.90) and PSC355 was a poor tester in this study with its hybrids averaging non-significant GCA effects for all traits except BOLWT and PLTHT. PSC355 exhibited negative GCA for BOLWT and positive GCA for PLTHT, neither of which are desirable for the anticipated phenotype of choice for future production in India. The combining ability portion of this study supported the general conclusions and observations of the raw data report above.

The GCA trends revealed that parental lines can be selected for line development programs to reduce plant height and improve yield, fiber quality and other agronomic traits in the development of F_1 hybrids for mechanical harvest in India. Tamcot 73, UA48 and Tamcot Sphinx were good combiners for YLD, fiber qualities and reduced PLTHT.

Among the Tamcot Sphinx line hybrids, positive SCA effects were detected for GA 161/ Tamcot Sphinx and All Tex 7A21/Tamcot Sphinx for YLD (Table 16). However, the GA 161/Tamcot Sphinx combination resulted in undesirable SCA effect for SL and the All Tex 7A21/Tamcot Sphinx combination reduced STR by an average of 11.85 kN m kg^{-1} below the mean of all combinations. The other hybrids for which significant and positive SCA effects were recorded were Lone Star / Tamcot Sphinx for BOLWT (0.59 g), SL (0.68 mm), STR (15.04 kN m kg^{-1}) and ELONG (0.16), and Deltatype Webber/ Tamcot Sphinx for STR (21.71 kN m kg^{-1}). TAM 0155/Tamcot Sphinx (-7.09 cm), MD 51ne/Tamcot Sphinx (-6.87 cm) and Rex/Tamcot Sphinx (-4.48 cm) combined for a desirable negative SCA effect for PLTHT. The two line parents that were identified as the most desirable based on GCA, Tamcot 73 and UA48 did not combine specifically with Tamcot Sphinx for any particular trait in a positive direction except for Tamcot 73/Tamcot Sphinx for improved GINOT at 1.06 per cent.

MD 51ne/TAM94L-25 exhibited positive and significant SCA for YLD (173.40 kg ha^{-1}), SDINX (0.80 g) and STR (15.14 kN m kg^{-1}). MD 51 ne is from the USDA program directed by the late Dr. Bill Meredith and was known for germplasm with improved STR. Specific combinations such as CS8606/TAM94L-25 for SL (0.85 mm) and BOLWT (0.38 g); TAM 73840/TAM94L-25 (22.20 kN m kg^{-1}) for STR; Acala Maxxa/TAM94L-25 (0.31) and DP16/TAM94L-25 (0.26) for MIC; TAM88G-104/TAM94L-25 (1.13 g) for SDINX; UA48/TAM94L-25 for (-6.02 cm) PLTHT resulted in significant SCA effects. Eight lines combined specifically with Tamcot 94L-25 for positive and significant improvement in GINOT. UA48, which exhibited the second most OVCNT numerically and which combined specifically with Tamcot Sphinx for an average reduction in OVCNT of 1.31 ovules, combined specifically with TAM 94L-25 for a significant and positive increase in OVCNT of 0.98 ovules.

PSC355 was selected as a tester based on its yield record in the US and was expected to combine with the lines in this study for improved yield and yield related traits. However, it was not identified as having good GCA (Table 15) and it combined specifically with only one line, DES 422, for a positive SCA element for YLD (Table 16). That combination also resulted in a significant SCA element of 0.46 g in BOLWT but a decrease of 1.32 % in GINOT. Combinations based on PSC355 exhibited non-significant SCA for SL and there were no SCA effects that were positive and significant for STR. PSC355 does not appear to be a good parent for improving yield, yield related traits such as GINOT, or HVI fiber properties.

Table 16. SCA effects from line x tester analysis for 90 upland cotton hybrids across Aurangabad and Hyderabad, India 2015.

Line/Tester	OVCNT†			SDCNT			YLD			BOLWT		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Lone Star	1.12*	-1.11*	-0.01	-0.13	1.05	-0.96	87.47	20.38	-107.43	0.59**	-0.10	-0.50**
Deltatype Webber	0.81	0.06	-0.87	-0.31	-0.53	0.80	-68.70	-22.46	91.40	-0.07	0.19	-0.13
Lightning Express	0.03	-0.46	0.43	-0.71	-1.45*	2.12**	12.55	-127.46*	114.74	-0.21	-0.15	0.35*
Mebane	-0.39	-0.29	0.68	-0.37	-0.29	0.63	-61.81	-10.15	72.04	-0.06	0.04	0.02
Rex	0.31	-0.23	-0.08	0.81	-0.19	-0.65	118.89	-76.96	-41.43	0.07	0.03	-0.10
Auburn 56	-0.04	0.13	-0.09	-0.57	0.05	0.48	-70.89	-41.32	112.54	0.00	0.07	-0.07
Stoneville 213	-0.10	0.9	-0.8	1.90**	0.87	-2.81**	-47.45	106.29	-59.01	-0.18	0.22	-0.04
DP16	0.54	-0.86	0.32	1.14*	-1.64**	0.46	76.64	-36.29	-39.93	0.13	-0.32*	0.19
Delcot 277	-0.84	0.65	0.19	-0.49	-0.15	0.60	-40.36	-32.46	73.07	-0.44**	0.35*	0.09
DES 422	0.76	-1.11*	0.34	0.01	0.16	-0.20	1.14	-183.46**	181.65**	0.15	-0.61**	0.46**
DP90	-0.06	-0.20	0.25	1.44*	-0.66	-0.82	-47.47	-32.49	79.71	0.17	0.23	-0.40*
DP50	-0.56	0.53	0.03	-0.98	0.72	0.22	-74.81	69.76	4.46	-0.12	0.08	0.04
SC1	-0.54	0.2	0.34	-1.52*	1.36*	0.12	-71.59	-52.43	123.51	0.09	0.10	-0.20
PD6520	-0.20	0.31	-0.12	1.69**	-1.30*	-0.43	-10.20	-2.29	11.57	-0.19	-0.04	0.22
CS8606	-0.14	0.23	-0.09	-0.02	0.64	-0.65	-95.25	23.07	71.10	-0.27	0.38*	-0.11
TAM 0155	-0.55	0.74	-0.19	0.13	-0.38	0.21	10.83	54.57	-65.74	-0.03	0.00	0.02
TAM 73840	0.11	-0.15	0.04	-0.15	0.01	0.10	-128.14*	93.51	35.71	-0.19	-0.11	0.30*
LA 887	-0.64	0.65	-0.01	-0.48	0.77	-0.33	80.66	-74.76	-5.49	0.21	-0.11	-0.11
MD 51ne	0.64	-0.25	-0.38	0.88	0.31	-1.22*	-31.59	173.40*	-142.32*	0.31*	-0.05	-0.26
Ciano Alamos 92	-0.13	-0.61	0.74	0.10	-0.59	0.45	90.11	-33.24	-56.04	0.18	-0.08	-0.10
Ciano Cocorim 92	0.01	-0.11	0.10	-0.74	0.21	0.50	14.69	85.10	-99.37	0.12	0.14	-0.27
TAM 86 GGG-30	-0.05	0.15	-0.10	-0.90	-0.18	1.04	-46.89	29.35	17.79	0.02	0.02	-0.05
Acala Maxxa	-0.23	0.20	0.03	-0.16	-0.26	0.39	-46.72	59.10	-12.87	-0.20	0.08	0.11
CS8601	0.79	0.30	-1.08*	-1.41*	0.62	0.75	-101.61	82.13	19.32	-0.24	-0.05	0.29
Acala 1517-99	0.55	-0.65	0.10	0.50	-0.78	0.24	-68.75	67.90	0.51	0.01	0.13	-0.14
GA 161	-0.04	-0.36	0.40	-0.69	0.52	0.13	251.05**	-67.29	-182.60**	0.14	-0.38*	0.24
TAM 88G-104	0.02	-0.46	0.44	0.55	-0.42	-0.17	71.41	12.24	-83.07	-0.15	0.25	-0.1
Tamcot 73	0.26	0.88	-1.14*	1.05	1.05	-2.13**	-3.59	-42.35	46.10	-0.15	-0.07	0.21
All Tex 7A21	-0.15	-0.04	0.19	0.58	-0.89	0.28	225.75**	-69.68	-156.24*	0.15	-0.27	0.11
UA48	-1.31**	0.98*	0.33	-1.50*	1.00	0.47	-24.06	26.76	-3.54	0.13	-0.02	-0.11
SE (SCA effects)	0.55	0.55	0.55	0.66	0.66	0.66	76.35	76.35	76.35	0.17	0.17	0.17

*Significantly different than zero at P=0.05
** Significantly different than zero at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield (kg ha^{-1}); BOLWT=Boll weight (g).

Table 16. Continued.

Line/Tester	PLTHT†			GINOT			SDINX		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
Lone Star	-0.09	-0.74	0.82	-0.45	-0.17	0.60	0.26	0.24	-0.52
Deltatype Webber	4.08	1.09	-5.18*	-1.64**	-0.33	1.95**	0.42	0.07	-0.52
Lightning Express	2.47	-1.85	-0.63	-0.12	-0.41	0.51	0.12	-1.31**	1.17**
Mebane	-0.31	-1.79	2.09	-0.19	0.24	-0.07	0.09	0.66*	-0.77*
Rex	-4.48*	2.21	2.26	-0.31	-0.07	0.35	0.04	-0.06	0.01
Auburn 56	0.47	0.32	-0.79	-0.13	-0.47	0.58	0.87**	-0.15	-0.74*
Stoneville 213	5.02*	2.04	-7.07**	-0.19	-1.45**	1.61**	0.04	-0.48	0.42
DP16	2.69	-0.13	-2.57	1.14**	0.22	-1.39**	-0.44	0.46	-0.05
Delcot 277	-2.53	1.98	0.54	-0.24	0.94*	-0.72	0.54	-0.56*	0.01
DES 422	-1.64	-2.96	4.59*	0.24	1.05*	-1.32**	0.09	-0.18	0.06
DP90	-3.20	1.48	1.71	-0.97*	0.89*	0.05	0.01	-0.43	0.40
DP50	5.63*	-0.02	-5.63*	-1.10**	0.96*	0.12	0.04	0.27	-0.33
SC1	3.19	-0.13	-3.07	-0.27	-0.47	0.72	-0.46	0.10	0.34
PD6520	-1.09	-3.24	4.32	-0.62	1.03*	-0.44	-0.33	0.24	0.06
CS8606	0.08	0.09	-0.18	-0.32	-0.46	0.75	0.45	-0.31	-0.16
TAM 0155	-7.09**	4.43	2.65	0.78*	1.25**	-2.06**	-0.55	-0.65*	1.17**
TAM 73840	-1.09	-3.91	4.98*	-0.42	0.19	0.21	0.34	0.24	-0.60*
LA 887	-1.98	3.37	-1.41	0.89*	-0.40	-0.51	-0.21	0.19	0.01
MD 51ne	-6.87**	2.15	4.71*	0.48	-0.12	-0.38	-0.44	0.80**	-0.38
Ciano Alamos 92	-0.59	-1.07	1.65	-0.24	-1.08**	1.30**	-0.21	0.02	0.17
Ciano Cocorim 92	-2.53	2.98	-0.46	0.02	-0.57	0.52	-0.41	-0.51	0.90**
TAM 86 GGG-30	-0.98	0.54	0.43	0.63	-0.25	-0.40	-0.52	0.38	0.12
Acala Maxxa	1.19	-1.29	0.09	0.73	0.30	-1.05*	-0.30	0.52	-0.24
CS8601	3.02	-0.46	-2.57	-0.48	1.13**	-0.68	0.15	-0.04	-0.13
Acala 1517-99	-2.03	1.32	0.71	-0.3	0.41	-0.13	0.12	-0.31	0.17
GA 161	-0.92	3.59	-2.68	1.06*	-1.61**	0.53	0.06	-0.20	0.12
TAM 88G-104	2.86	0.21	-3.07	0.25	0.10	-0.38	-0.69*	1.13**	-0.46
Tamcot 73	1.08	-3.41	2.32	1.06*	-2.01**	0.93*	0.37	-0.48	0.09
All Tex 7A21	3.41	-0.91	-2.52	-0.08	1.25**	-1.19**	0.23	0.13	-0.38
UA48	2.13	-6.02*	3.87	0.54	-0.30	-0.26	0.12	0.02	-0.16
SE (SCA effects)	2.68	2.68	2.68	0.45	0.45	0.45	0.33	0.33	0.33

*Significantly different than zero at P=0.05
** Significantly different than zero at P=0.01
† PLTHT=Plant height (cm); GINOT=Ginning out turn (%); SDINX=Seed index (g).

Table 16. Continued.

Line/Tester	SL†			STR			MIC			UR			ELONG		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Lone Star	0.68*	-0.59	-0.10	15.04*	-4.39	-11.74	-0.03	0.00	0.03	-0.58*	0.32	0.24	0.16**	-0.16**	-0.01
Deltatype Webber	0.19	-0.06	-0.13	21.71**	-6.39	-16.36*	0.12	0.04	-0.16	-0.49	0.00	0.47	-0.02	0.06	-0.04
Lightning Express	-0.13	-0.39	0.52	7.93	-12.82*	3.79	-0.14	-0.33**	0.47**	-0.23	0.12	0.10	0.05	-0.07	0.01
Mebane	-0.01	-0.11	0.12	-1.00	6.38	-6.46	0.00	-0.15	0.15	0.37	-0.21	-0.18	-0.02	0.03	-0.01
Rex	-0.21	0.46	-0.25	-1.74	1.24	-0.60	0.32**	-0.22*	-0.10	-0.29	-0.36	0.63*	-0.05	-0.07	0.11*
Auburn 56	-0.30	0.27	0.03	-3.89	-0.57	3.38	0.04	-0.14	0.09	0.00	0.02	-0.04	-0.07	-0.02	0.09
Stoneville 213	0.54	-0.22	-0.32	-3.60	-0.88	3.33	0.24**	-0.08	-0.16*	0.48	-0.12	-0.37	0.21**	-0.06	-0.16**
DP16	0.30	-0.25	-0.06	-3.26	-1.88	4.05	-0.25**	0.26**	-0.01	-0.64*	0.36	0.27	-0.10	0.03	0.06
Delcot 277	0.21	-0.23	0.01	-6.74	5.33	0.32	0.24**	-0.01	-0.23*	0.33	0.14	-0.48	0.12*	0.05	-0.17**
DES 422	-0.08	-0.3	0.38	13.86*	-6.58	-8.33	-0.04	0.05	-0.02	0.12	0.46	-0.59*	0.05	-0.19**	0.14*
DP90	0.01	-0.24	0.23	-20.91**	10.55	9.22	-0.29**	0.00	0.28**	-0.01	-0.09	0.09	-0.09	0.07	0.02
DP50	0.38	-0.42	0.04	4.49	-10.52	4.95	-0.07	0.02	0.05	-0.18	0.00	0.16	-0.14*	-0.06	0.19**
SC1	0.17	0.41	-0.59	-4.14	5.79	-2.79	0.02	0.02	-0.05	0.10	-0.31	0.20	-0.01	0.05	-0.05
PD6520	-0.34	0.32	0.02	-11.98*	9.46	1.44	-0.24**	0.00	0.24**	0.21	-0.2	-0.02	0.02	0.05	-0.07
CS8606	-0.38	0.85**	-0.47	-7.70	-0.55	7.17	0.12	-0.11	-0.01	0.69*	-0.49	-0.22	-0.02	0.07	-0.06
TAM 0155	-0.42	-0.08	0.49	11.28	0.48	-12.83*	0.14	-0.14	-0.01	0.08	-0.08	-0.02	0.01	0.07	-0.08
TAM 73840	0.62*	-0.62*	-0.01	-17.14**	22.20**	-6.12	0.01	0.16	-0.17*	-0.51	0.27	0.23	-0.08	0.07	0.00
LA 887	0.16	0.03	-0.19	3.18	0.36	-4.65	-0.07	0.13	-0.06	-0.28	-0.21	0.47	0.06	-0.08	0.02
MD 51ne	-0.15	0.26	-0.11	-3.22	15.14*	-13.02*	-0.17*	0.12	0.05	-0.10	0.31	-0.23	-0.13*	0.07	0.05
Ciano Alamos 92	-0.16	-0.03	0.18	-1.03	0.11	-0.17	-0.10	-0.16	0.25**	0.13	-0.12	-0.03	0.01	-0.06	0.04
Ciano Cocorim 92	-0.27	-0.14	0.41	-14.69*	6.55	7.14	0.10	0.02	-0.12	0.23	0.22	-0.47	-0.02	0.03	-0.01
TAM 86 GGG-30	-0.45	0.34	0.12	-1.40	6.80	-6.48	0.05	0.06	-0.11	-0.22	-0.14	0.35	-0.07	0.01	0.06
Acala Maxxa	0.55	-0.44	-0.12	11.62	-1.05	-11.56	-0.23**	0.31**	-0.08	-0.27	0.44	-0.18	0.00	-0.09	0.09
CS8601	-0.51	0.33	0.18	1.26	-3.18	0.84	-0.04	0.06	-0.02	0.14	-0.56*	0.41	-0.07	0.02	0.04
Acala 1517-99	0.58	-0.90**	0.33	11.45	8.93	-21.47**	0.06	-0.05	-0.01	-0.13	0.4	-0.28	0.06	-0.03	-0.03
GA 161	-0.69*	0.74*	-0.05	-5.35	1.16	3.04	0.23**	-0.17*	-0.07	0.22	-0.21	-0.02	-0.07	0.09	-0.03
TAM 88G-104	-0.16	0.30	-0.14	6.66	1.13	-8.89	-0.07	0.19*	-0.12	0.51	-0.47	-0.05	0.05	0.04	-0.09
Tamcot 73	0.56	-0.12	-0.44	-0.47	11.40	-12.00*	-0.03	-0.07	0.10	-0.22	0.15	0.06	0.05	0.01	-0.06
All Tex 7A21	-0.05	0.15	-0.10	-11.85*	9.84	0.92	-0.04	0.10	-0.06	0.28	0.02	-0.32	-0.03	0.02	0.00
UA48	-0.65*	0.65*	0.00	11.69	8.57	-21.36**	0.12	0.05	-0.17*	0.11	0.18	-0.30	0.09	0.00	-0.10
SE (SCA effects)	0.35	0.35	0.35	7.11	7.11	7.11	0.09	0.09	0.09	0.32	0.32	0.32	0.06	0.06	0.06

*Significantly different than zero at P=0.05

** Significantly different than zero at P=0.01

† SL= Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UR= Uniformity ratio; ELONG=Fiber elongation. Abbreviations- T1=Tamcot Sphinx, T2=TAM94L-25, T3=PSC355

US locations

<u>Parental evaluations</u>

Performance of the 30 lines and three testers used in the line x tester analysis plus three control experimental strains from the Cotton Improvement Lab at Texas A&M AgriLife Research plus DP491 control as a recent high quality cultivar and Tamcot 73 control, for a total of 38 genotypes were evaluated for boll, agronomic, and HVI fiber properties at College Station in 2015 and presented herein to verify the variation in these lines and testers when grown in the US. Parental lines differed in their performance for all traits measured except OVCNT and ELONG, which supports the selection of these lines and testers for the present study (Table 17). Tamcot 73 was included as a separate control although it was one of the lines in the line x tester design and reported by Smith et al. (2011) as possessing excellent agronomic and fiber properties when grown in south Texas. The means of the lines and testers, along with the additional entries are summarized in Table 18.

Most of the parental lines and testers included in this study were not significantly different than the Tamcot 73 control but there was considerable variation observed that supports the choice of these genotypes for this study. The control genotype TAM 06WE-621 exhibited more ($P<0.05$) seeds per boll, SDCNT, than all other genotypes. This high SDCNT for TAM 06WE-621 was expected based on the release documentation in Smith et al. (2014). Acala 1517-99 averaged the numerically lowest SDCNT at 23 seeds per boll which was significantly lower than all genotypes except control TAM 13P-54.

GINOT varied considerably across the genotypes tested at College Station in 2015 with Lightning Express, released in 1936, having a lower (P=0.05) value than all other genotypes (Table 18). The more modern genotypes such as DP90, LA 887, All Tex 7A21, and DP 491 exhibited the higher GINOT values and along with Ciano Alamos 92, TAM 0155, TAM 73840 and DES 422, were significantly higher than the Tamcot 73 control. The remaining genotypes ranged from 29.8 % to 37.1% which is greater than the LSD value of 1.73 % and thus exhibits considerable significant variation.

The control genotype TAM 13P-54 exhibited the longest UHM of 36.7 mm (Table 18). This was expected as this experimental strain was developed as a part of the Texas A&M AgriLife Research Extra Long Staple Upland program, a program designed to develop *G. hirsutum* genotypes with *G. barbadense* type fiber length without introgression of *G. barbadense*. Among the lines and tester parental material, Acala Maxxa, UA48, and TAM 94L-25 were significantly longer than the Tamcot 73 check. Twelve genotypes were significantly shorter than the Tamcot 73 check.

TAM 06WE-621 was expected to have the strongest fibers and indicated by the HVI STR value of 393.3 kN m kg^{-1} (Table 18). Among the 33 lines and tester genotypes UA48, Tamcot 73, Acala 1517-99, LA 887and MD 51ne recorded significantly higher STR. CS8606 had the lowest STR at 246.2 kN m kg^{-1} which was significantly lower than all other line or tester genotypes. The remaining genotypes were intermediate to these high and low STR genotypes, again indicating a significant range in this trait among the selected lines and testers.

Unlike the data from the Indian locations, MIC of all genotypes when grown at College Station, TX had MIC values above the 3.5 minimum standard to indicate maturity and adequate secondary wall formation for spinning and dying, except for Lone Star that was developed in 1906 (Table 18). UI, a measure of length uniformity, values were as expected with little numerical variation, although there were extremes. TAM 13P-54 and TAM 06WE-621 checks, along with Delcot 277, released in 1972, exhibited significantly better UI than all other genotypes. The lowest UI was recorded for TAM 0155 which was significantly lower than all genotypes except TAM 73840. No significant differences were found for ELONG at College Station in 2015.

These parental values verify the appropriateness of the selected lines and testers for the line x tester study. Parental lines, e.g., UA48 and TAM94L-25, were observed to be better for UHM and STR in India and the US locations which indicates their stable performance for respective traits. UA48 overall demonstrated stable behavior for yield and fiber quality (Tables 6 and 18).

Table 17. Mean squares from analysis of variance for indicated traits in upland cotton parental genotypes at College Station, TX, US 2015.

S.O.V.	df	OVCNT†	SDCNT	GINOT	UHM	STR	MIC	UI	ELONG
Rep	1	38.03	7.06	1.91	0.88	700.62	0.03	0.02	2.96
Genotype	37	11.42	10.7**	15.35**	6.72**	2778.20**	0.42**	3.91**	1.96
Error	37	7.96	4.07	2.35	0.65	290.63	0.12	0.90	1.23
C.V. (%)		7.91	6.85	4.37	2.73	5.42	7.55	1.12	13.85

*Significant at P=0.05

** Significant at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; GINOT=Ginning out turn %; UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.

Table 18. Mean performance of select US upland cotton parental genotypes for indicated traits at College Station, TX, US, 2015.

Genotype	OVCNT†	SDCNT	GINOT	UHM	STR	MIC	UI	ELONG
	(No)	(No)	(%)	(mm)	(kN m kg^{-1})	(Unit)	(Index)	(%)
Lone Star	40.9	31.3	31.3	29.3	284.9	3.4	84.5	9.6
Deltatype Webber	35.6	28.6	29.9	27.9	270.7	4.3	83.1	10.0
Lightning Express	34.2	28.6	28.0	27.2	267.7	4.4	83.3	8.1
Mebane	31.8	26.2	34.7	26.9	276.1	5.2*	83.2	9.4
Rex	36.4	31.6	31.7	29.1	278.0	4.7	84.0	8.4
Auburn 56	39.0	30.7	29.7	30.2	290.8	4.5	83.8	9.1
Stoneville 213	35.2	31.8	35.6	29.0	282.4	5.0	84.1	7.6
DP16	38.1	33.2	35.2	30.1	288.3	4.7	84.1	9.1
Delcot 277	35.5	27.5	34.2	31.0	314.3	4.4	86.6*	9.1
DES 422	33.4	26.5	37.4*	29.1	278.0	4.6	84.2	6.6
DP90	36.0	31.6	38.2*	27.7	343.7	5.5*	82.6	6.6
DP 50	35.7	31.3	34.8	29.3	286.4	5.3*	84.6	7.4
SC1	33.9	28.4	36.9	28.8	323.6	5.1	84.9	7.3
PD6520	33.0	27.2	34.1	28.4	298.6	4.7	84.5	6.9
CS8606	39.9	29.0	35.9	27.9	246.2	4.6	82.4	8.0
TAM 0155	35.8	29.8	37.5*	28.1	278.0	4.3	81.0	8.9
TAM 73840	35.0	27.8	37.4*	27.8	274.1	4.4	81.9	7.8
LA 887	33.7	28.2	39.4*	30.0	365.8*	5.3*	84.9	9.0
MD 51ne	36.2	31.3	37.1	30.2	375.6*	5.4*	85.8	7.9
Ciano Alamos 92	38.3	30.3	38.0*	28.3	303.0	4.8	83.3	7.5

Table 18. Continued.

Genotype	OVCNT†	SDCNT	GINOT	UHM	STR	MIC	UI	ELONG
	(No)	(No)	(%)	(mm)	(kN m kg^{-1})	(Unit)	(Index)	(%)
Ciano Cocorim 92	36.5	31.7	35.1	29.7	307.9	4.6	84.1	6.3
TAM 86 GGG-30	31.9	27.7	31.2	27.7	296.7	4.4	84.1	11.0
Acala Maxxa	37.5	27.0	34.1	31.2*	332.9	4.0	86.2	8.4
CS8601	35.5	31.9	34.4	29.0	278.5	4.8	85.3	8.1
Acala 1517-99	30.9	23.0	35.3	29.1	389.8*	4.1	86.4	7.1
GA 161	33.2	28.9	35.6	29.8	323.6	4.9	84.8	7.6
TAM 88G-104	33.4	28.1	36.4	29.6	307.4	5.0	83.9	8.1
Tamcot 73	38.8	30.8	36.8	31.1*	375.1*	5.1	85.1	7.5
All Tex 7A21	34.0	28.4	39.6*	30.0	295.7	4.9	85.5	8.3
UA48	33.2	27.9	35.2	32.6*	380.0*	5.3*	85.6	7.0
Tamcot Sphinx	37.5	31.0	34.6	27.3	318.7	4.9	83.7	7.4
TAM 94L-25	36.1	29.6	33.5	32.6*	316.3	4.4	86.0	6.4
PSC355	34.6	29.2	36.7	29.2	334.9	5.3*	85.1	8.3
TAM 06WE-621	38.4	34.5*	36.0	31.2*	393.3*	4.6	87.1*	7.5
TAM 13P-54 ELSU	31.5	26.1	29.8	36.7*	349.1	3.6	87.7*	6.9
DP 491	39.3	34.2	38.4*	31.5*	328.0	4.3	83.6	7.4
TAM 13Q-18	38.4	33.1	37.0	31.5*	322.7	4.6	84.1	7.7
Tamcot 73 (Check)	37.5	31.2	35.6	30.0	344.7	4.9	85.2	7.2
LSD	ns	3.08	1.73	1.05	20.06	0.31	1.21	ns

*Significantly superior to Tamcot 73 (check) at P=0.05.

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; GINOT=Ginning out turn (%); UHM=Upper fiber mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.

Hybrid Evaluations

ANOVA was performed to test significance of differences among all genotypes including crosses and parents (lines and testers), as well as to understand performance compared to the standard check cultivar, Tamcot 73, when grown at Weslaco and College Station, TX in 2015 (Tables 19 - 21). Combined analysis for six traits common at both locations revealed significant differences among genotypes tested for all those traits. Genotype x Location interaction was also significant for UHM, suggesting differential behavior of genotypes across locations for UHM. Due to inclement weather at College Station in 2015 during maturation and harvest time, YLD and PLTHT were not measured and because of a communication error, OVCNT and SDCNT were recorded only for College Station. GINOT and HVI fiber properties were determined at both locations. Genotypes were significantly different for the traits YLD and PLTHT at Weslaco (Table 20) and OVCNT and SDCNT at College Station (Table 21).

At College Station and Weslaco, 90 hybrids were planted based on 30 lines and 3 testers. College Station included all 33 parents, whereas at Weslaco, the three testers and suitable checks were planted. Heterosis over best tester was calculated at both locations considering it as best available parent. Since combined ANOVA revealed significant Genotype x Location interaction for UHM and also both locations differed for parents included and traits measured, mean performance of hybrids and heterosis are summarized location wise for traits having significant Genotype x Location interaction or measured at single location and combined means for traits where Genotype x Location was non-significant and traits measured at both locations. (Table 22 and 23)

Table 19. Mean squares from combined analysis of variance for indicated traits in upland cotton at Weslaco and College Station, TX, US 2015.

S.O.V.	df	GINOT†	UHM	STR	MIC	UI	ELONG
Loc	1	95.29	1.53	28691.09**	1.94**	5.14	3.76
Rep (loc)	3	63.41	0.80	325.7	0.001	0.56	3.55
Genotype (Gen)	123	16.61**	6.66**	1775.9**	0.32**	2.66**	2.12**
Gen*Loc	94	1.97	0.81**	206.3	0.04	1.10	0.81
Error	307	3.33	0.50	188.26	0.04	0.85	0.60
C.V. (%)		5.07	2.34	4.40	4.58	1.08	10.98

*Significant at P=0.05
** Significant at P=0.01
† GINOT=Ginning out turn (%); UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.

Table 20. Mean squares from analysis of variance for indicated traits in upland cotton recorded only at Weslaco, TX, US 2015.

S.O.V.	df	YLD†	PLTHT
Rep	2	11546481.3	6035.6
Genotype	93	758204.4**	299.1**
Error	188	332459.3	82.12
CV (%)		12.78	8.38

*Significant at P=0.05
** Significant at P=0.01
† YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm).

Table 21. Mean squares from analysis of variance for indicated traits in upland cotton recorded only at College Station, TX, US 2015.

S.O.V.	df	OVCNT†	SDCNT
Rep	1	14.54	0.48
Genotype	123	10.10*	8.3*
Error	114	6.81	5.8
CV (%)		7.26	7.97

*Significant at P=0.05
** Significant at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll.

OVCNT and SDCNT were recorded at College Station (CS) only. None of F_1 hybrids were found superior to Tamcot 73 for either of these traits (Table 22). OVCNT ranged between 32.1 to 42.6 and SDCNT from 26.7 to 35.6. Mean of OVCNT over 90 hybrids was 36.1 while SDCNT was 30.9, indicating that on an average five ovules were aborted during boll development or were not fertilized. There is a possibility that genotypes that retain more seeds would produce higher seed cotton and lint yields. Since these traits are difficult to measure and prone to error, marker based selection could be useful. Only two F_1 hybrids, Lone Star/Tamcot Sphinx and Deltatype Webber/PSC355, had positive significant heterosis for OVCNT, while only Mebane/PSC355, DP16/Tamcot Sphinx and CS8601/Tamcot Sphinx had positive significant heterosis for SDCNT. Average OVCNT and SDCNT across combinations of common testers did not differ significantly indicating testers did not impact these traits in hybrid combinations.

YLD and PLTHT were recorded only at Weslaco. For YLD, only one hybrid combination i.e., Tamcot 73/PSC355 (6377 kg ha^{-1}) was significantly superior to Tamcot 73 (5161 kg ha^{-1}) and exhibited the highest heterosis of 72.1%. Heterosis range was -8.1% to 72.1% across all ninety hybrids indicating the range of possibilies for hybrid breeding in compact x compact genotypes. Twenty-two F_1 hybrids had highly significant heterosis (significant at P=0.01) for YLD while 12 genotypes were significant at P=0.05. Among these 34 genotypes which recorded significant heterosis for YLD, 19 entries had TAM94L-25 as tester indicating the value of this line for heterosis breeding for YLD apart from improving fiber quality. On the other side Tamcot Sphinx based hybrid combinations averaged to 4726 kg ha^{-1} YLD at Weslaco which was significantly high as compared to PSC355 and Tamcot 94L-25 combinations indicating better breeding value for Tamcot Sphinx for YLD.

Reduced plant height is a preferred phenotypic trait for high density planting. Only one F_1 hybrid TAM 0155/TAM94L-25 (76.3 cm) was significantly shorter that Tamcot 73 (101.1 cm), however 20 other F_1 hybrids had numerically lower PLTHT than the check (Table 22). Heterosis ranged from -20.2% to 23.8% and thirty-one entries recorded negative heterosis for PLTHT, two of them being significant. TAM94L-25 based hybrids averaged to 101 cm for PLTHT which was comparable to Tamcot 73 while PSC355 combinations had mean PLTHT of 116 cm. This indicates careful selection of parents is required to lower PLTHT while maintaining YLD and fiber qualities.

GINOT was recorded was both locations and had non-significant Genotype x Location interaction (Table 19) hence mean performance of the hybrids was calculated over locations (Table 22). All Tex 7A21/Tamcot Sphinx and All Tex 7A21/PSC355 were significantly superior for GINOT compared with Tamcot 73 (Table 22). Heterosis ranged from -12.9% to 9.7%. Four and 27 hybrid entries exhibited positive and negative significant heterosis. Mean GINOT for TAM 94L-25 based hybrids across location was 34.6% which was lower than the varietal check. This may be due to heavier seed weight observed for TAM94L-25 at Indian locations.

Table 22. Mean performance and heterobeltiosis based on best performing parent for 90 F_1 upland cotton hybrids for yield and agronomic traits grown at Weslaco and College Station, TX, US, 2015.

Hybrid Combination	CS		CS		WS		WS		Combined CS and WS	
	OVCNT†	Hb%‡	SDCNT	Hb%	YLD	Hb%	PLTHT	Hb%	GINOT	Hb%
	(No)		(No)		(kg ha^{-1})		(cm)		(%)	
Lone Star/ Sphinx	42.6	13.5*	34.7	12.1	3905	-8.1	110.9	0.8	34.6	-8.9**
Lone Star/94L-25	38.5	6.6	31.4	6.2	3813	10.6	113.9	21.0**	32.9	-3.9
Lone Star/PSC355	36.9	6.6	32.8	12.3	3640	-1.8	137.3	21.7**	35.2	-10.0**
Deltatype Webber/Sphinx	35.4	-5.7	30.7	-1.0	5048	18.8	115.2	4.8	33.1	-12.9**
Deltatype Webber/94L-25	35.1	-2.8	30.8	4.1	3892	12.9	107.7	14.4*	31.9	-6.8*
Deltatype Webber/PSC355	40.0	15.5*	32.5	11.1	4199	13.3	130.4	15.6**	34.1	-12.8**
Lightning Express/ Sphinx	39.9	6.4	32.2	4.0	5309	24.9*	112.9	2.6	33.8	-11.1**
Lightning Express/94L-25	35.3	-2.4	32.1	8.6	4353	26.2*	106.3	13.0	32.5	-5.1
Lightning Express/PSC355	35.1	1.4	31.8	8.7	4193	13.2	124.0	9.9	35.0	-10.5**
Mebane/Sphinx	38.0	1.2	28.3	-8.6	4599	8.2	110.1	0.1	36.2	-4.7
Mebane/94L-25	37.4	3.5	32.0	8.1	3868	12.2	109.3	16.2*	34.1	-0.7
Mebane/PSC355	37.8	9.3	33.9	16.1*	3923	5.9	108.5	-3.9	37.1	-5.3*
Rex/Sphinx	37.7	0.5	30.2	-2.4	4495	5.8	106.2	-3.4	35.2	-7.4**
Rex/94L-25	38.6	6.9	33.3	12.7	4077	18.2	99.3	5.6	34.0	-0.9
Rex/PSC355	33.9	-1.9	29.2	-0.1	4308	16.3	118.0	4.6	36.2	-7.5**
Auburn 56/Sphinx	37.4	-0.4	33.5	8.1	4816	13.3	115.6	5.1	33.9	-10.8**
Auburn 56/94L-25	33.3	-7.8	26.7	-9.8	5190	50.5**	106.4	13.1	32.6	-5.0
Auburn 56/PSC355	33.9	-2.0	30.3	3.8	4326	16.8	111.3	-1.3	35.5	-9.3**
Stoneville 213/Sphinx	33.9	-9.6	30.4	-1.8	4344	2.2	109.3	-0.6	38.6	1.7
Stoneville 213/94L-25	36.8	1.9	32.9	11.3	4356	26.3*	111.3	18.2**	34.1	-0.6
Stoneville 213/PSC355	36.5	5.5	31.2	7.0	4325	16.7	122.4	8.4	36.5	-6.8**
DP16/ Sphinx	39.3	4.8	35.6	14.9*	4379	3.0	110.1	0.1	36.9	-2.9
DP16/94L-25	37.9	4.8	32.9	11.3	4997	44.9**	99.2	5.4	34.3	0.0
DP16/PSC355	35.9	3.8	29.4	0.7	4826	30.2**	115.1	2.0	37.8	-3.6
Delcot 277/ Sphinx	33.9	-9.7	30.7	-1.0	4635	9.1	113.7	3.3	36.2	-4.7
Delcot 277/94L-25	36.7	1.7	31.7	7.3	4311	25.0*	108.1	14.9*	33.9	-1.2
Delcot 277/PSC355	34.5	-0.4	27.5	-5.8	4649	25.5*	114.9	1.8	35.2	-10.0**
DES 422/ Sphinx	38.7	3.2	31.0	0.2	4517	6.3	103.3	-6.0	37.5	-1.3
DES 422/ 94L-25	33.2	-8.0	30.5	3.2	4350	26.1*	93.6	-0.6	34.3	0.0
DES 422/PSC355	37.4	8.1	31.4	7.5	NA	NA	124.7	10.5	37.0	-5.5*
DP90/Sphinx	34.9	-6.9	28.9	-6.6	4843	13.9	115.2	4.8	38.7	1.7
DP90/ 94L-25	32.2	-10.8	28.1	-5.1	4869	41.2**	115.1	22.3**	35.2	2.7
DP90/PSC355	35.7	3.2	32.2	10.4	4427	19.5	122.4	8.5	36.3	-7.3**

Table 22. Continued.

Hybrid Combination	CS		CS		WS		WS		Combined CS and WS	
	OVCNT†	Hb%‡	SDCNT	Hb%	YLD	Hb%	PLTHT	Hb%	GINOT	Hb%
	(No)		(No)		(kg ha^{-1})		(cm)		(%)	
DP50/Sphinx	39.4	4.9	33.2	7.1	5572	31.1**	112.1	2.0	36.6	-3.8
DP50/ 94L-25	38.8	7.3	33.4	12.9	4650	34.8**	97.0	3.1	34.7	1.1
DP50/PSC355	36.4	5.1	32.5	11.1	4785	29.1**	114.1	1.1	37.3	-4.8
SC1/ Sphinx	33.3	-11.3	28.2	-8.9	4674	10.0	105.8	-3.8	37.4	-1.6
SC1/ 94L-25	35.6	-1.5	30.2	2.0	3856	11.8	95.3	1.3	34.9	1.9
SC1/PSC 355	37.0	6.9	31.9	9.1	4257	14.9	112.5	-0.3	37.4	-4.4
PD6520/ Sphinx	39.4	4.9	32.8	6.0	5532	30.2**	105.1	-4.4	36.5	-4.0
PD6520/ 94L-25	33.8	-6.5	29.7	0.5	4171	21.0	98.9	5.1	34.9	1.8
PD6520/PSC355	34.7	0.3	29.8	1.9	3837	3.6	112.3	-0.5	37.4	-4.5
CS8606/ Sphinx	37.9	1.1	32.5	5.0	4561	7.3	109.1	-0.8	37.3	-1.9
CS8606/ 94L-25	33.0	-8.6	28.9	-2.2	4954	43.7**	98.7	4.8	36.0	5.1
CS8606/PSC355	35.6	2.9	30.9	5.7	4345	17.3	106.6	-5.5	38.4	-2.0
TAM 0155/Sphinx	40.5	7.9	31.6	1.9	4829	13.6	104.1	-5.3	36.0	-5.2*
TAM 0155/ 94L-25	37.4	3.5	31.7	7.3	3453	0.1	76.3*	-18.9**	35.6	3.8
TAM 0155/PSC355	36.0	3.9	30.4	3.9	4498	21.4	108.7	-3.7	38.4	-2.1
TAM 73840/ Sphinx	37.1	-1.1	30.7	-1.0	4181	-1.6	87.8	-20.2**	37.4	-1.6
TAM 73840/ 94L-25	38.5	6.6	33.4	12.9	4579	32.8**	88.9	-5.5	35.4	3.3
TAM 73840/PSC355	32.2	-7.1	26.8	-8.2	3992	7.7	102.0	-9.6	39.1	-0.2
LA 887/ Sphinx	37.9	1.1	32.8	6.0	5028	18.3	110.9	0.8	38.5	1.3
LA 887/94L-25	34.7	-3.9	29.4	-0.5	4994	44.8**	116.5	23.8**	37.0	8.1**
LA 887/PSC355	38.4	11.0	32.3	10.4	5115	38.1**	123.3	9.3	39.8	1.7
MD 51ne/ Sphinx	33.1	-11.7	29.1	-6.0	4821	13.4	115.3	4.9	37.0	-2.7
MD 51ne/ 94L-25	34.5	-4.4	29.4	-0.5	4587	33.0**	92.4	-1.8	36.1	5.4
MD 51ne/PSC355	34.8	0.4	31.5	7.8	4800	29.6**	119.3	5.8	39.6	1.0
Ciano Alamos 92/ Sphinx	38.7	3.1	30.7	-1.0	4122	-3.0	102.5	-6.8	37.5	-1.4
Ciano Alamos 92/ 94L-25	38.7	7.1	33.0	11.5	3912	13.4	95.8	1.8	36.0	4.9
Ciano Alamos 92/PSC355	35.3	1.9	31.1	6.3	4830	30.3**	115.2	2.1	38.8	-1.0
Ciano Cocorim 92/ Sphinx	38.4	2.4	30.7	-1.0	4623	8.8	104.9	-4.7	37.2	-2.3
Ciano Cocorim 92/94L-25	35.8	-0.8	31.4	6.1	4703	36.4**	98.5	4.7	36.1	5.3
Ciano Cocorim 92/PSC355	35.6	2.9	30.8	5.3	4731	27.7*	117.0	3.7	36.6	-6.6*
TAM 86 GGG-30/ Sphinx	35.6	-5.2	29.0	-6.5	4118	-3.1	108.1	-1.7	34.0	-10.4**
TAM 86 GGG-30/94L-25	32.1	-11.1	27.8	-6.1	4095	18.7	98.0	4.1	33.6	-2.0
TAM 86 GGG-30/PSC355	38.3	10.7	31.4	7.4	4350	17.4	114.6	1.6	34.4	-12.2**

Table 22. Continued.

Hybrid Combination	CS		CS		WS		WS		Combined CS and WS	
	OVCNT†	Hb%‡	SDCNT	Hb%	YLD	Hb%	PLTHT	Hb%	GINOT	Hb%
	(No)		(No)		(kg ha^{-1})		(cm)		(%)	
Acala Maxxa/ Sphinx	38.4	2.4	33.0	6.6	4676	10.0	110.2	0.2	35.7	-6.2*
Acala Maxxa/94L-25	35.0	-3.1	29.3	-0.9	4052	17.5	89.5	-4.9	33.9	-1.3
Acala Maxxa/PSC355	33.0	-4.6	29.4	0.7	3682	-0.6	100.7	-10.8	35.3	-10.0**
CS8601/ Sphinx	39.6	5.5	35.3	14.1*	4770	12.2	99.4	-9.6	35.1	-7.8**
CS8601/ 94L-25	39.4	9.0	32.1	8.5	4171	21.0	105.3	11.9	33.1	-3.4
CS8601/PSC355	33.4	-3.6	29.5	0.9	4679	26.3*	104.8	-7.1	36.8	-6.1*
Acala 1517-99/ Sphinx	34.6	-7.9	30.5	-1.6	4996	17.5	114.0	3.6	36.3	-4.5
Acala 1517-99/ 94L-25	34.8	-3.7	26.9	-9.1	4661	35.1**	109.9	16.8*	34.4	0.4
Acala 1517-99/PSC355	36.7	6.0	29.1	-0.4	4227	14.1	120.7	6.9	35.7	-8.7**
GA 161/ Sphinx	36.8	-1.9	32.2	4.0	5041	18.6	113.2	2.9	37.3	-1.8
GA 161/ 94L-25	32.4	-10.2	28.7	-2.9	4903	42.2**	99.9	6.1	35.0	2.1
GA 161/PSC355	35.5	2.5	30.3	3.8	4114	11.0	126.6	12.2*	38.7	-1.3
TAM 88G-104/ Sphinx	33.7	-10.1	30.1	-2.9	4745	11.6	107.8	-2.0	36.3	-4.5
TAM 88G-104/ 94L-25	36.9	2.1	32.4	9.5	5092	47.6**	103.1	9.6	33.5	-2.4
TAM 88G-104/PSC355	34.4	-0.6	28.4	-2.9	4714	27.2*	125.2	11.0	37.0	-5.5*
Tamcot 73/ Sphinx	36.8	-1.9	30.0	-3.1	4735	11.4	99.0	-10.0	38.2	0.4
Tamcot 73/94L-25	36.6	1.4	30.8	4.1	4960	43.8**	104.7	11.3	35.6	3.7
Tamcot 73/PSC355	34.2	-1.1	32.3	10.7	6377*	72.1**	112.2	-0.6	36.7	-6.4*
All Tex 7A21/ Sphinx	33.3	-11.3	29.4	-5.0	5318	25.1*	110.9	0.8	41.7*	9.7**
All Tex 7A21/ 94L-25	34.6	-4.2	30.1	1.9	4510	30.8*	99.9	6.2	37.1	8.2**
All Tex 7A21 /PSC355	34.9	0.9	30.9	5.8	4516	21.9	117.3	4.0	41.3*	5.4*
UA48/ Sphinx	35.9	-4.4	32.5	5.0	4554	7.2	104.1	-5.3	37.7	-0.8
UA48/TAM 94L-25	34.3	-5.0	30.3	2.4	4408	27.8*	91.9	-2.4	35.0	2.0
UA48/PSC355	33.5	-3.2	27.3	-6.5	4874	31.5**	122.0	8.1	37.4	-4.4
Tamcot 73 (check)	37.4		31.2		5161		101.1		37.04	

*Significant at P=0.05 (For mean comparison with Tamcot 73 and heterosis different than zero)

** Significant at P=0.01 (For mean comparison with Tamcot 73 and heterosis different than zero)

† OVCNT=No of ovules per boll; SDCNT=No of seeds per boll; PLTHT=Plant height (cm); YLD=Seed cotton yield kg ha^{-1}; GINOT=Ginning out turn (%)

‡ Hb% i.e. heterobeltiosis for respective trait measured.

Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25, CS=College Station, WS=Weslaco

Significant Genotype x Location interaction was observed for UHM hence location wise mean performance is presented for UHM (Table 23). UHM ranged from 27.9 mm to 33.4 mm at CS and 28.3 mm to 33.9 mm at WS among the 90 hybrids. Twenty four hybrids at CS and two at WS were significantly longer than Tamcot 73 with the F_1 hybrids GA 161/TAM94L-25 and UA48/TAM94L-25 being significantly longer at both locations. Heterosis for UHM ranged between -8.6% to 15.3% at CS and -10.9% to 15.6% at WS. Thirty five hybrids had significant positive heterosis for UHM at CS while 44 were positively significant at WS. As expected TAM94L-25 based F_1 combinations had average UHM of 31.6 at both the locations which were comparable to check and higher than other two tester based hybrids.

For STR, combined performance over location revealed that none of the hybrid combination outperformed Tamcot 73; however, 12 entries exhibited significant and positive heterosis (Table 23). Heterosis ranged between -25.5% and 11.5%. Close scrutiny of data revealed that hybrids having TAM94L-25 as tester had mean STR of 316 kN m kg^{-1}. This indicates that TAM94L-25 can be used for better UHM and STR in hybrid combinations.

MIC range was 3.9 to 5.1 when mean performance of the hybrids was calculated over both locations. Four entries had significant superior MIC compared to Tamcot 73. Thirty one hybrids exhibited MIC equal or greater than 4.9. Heterosis ranged between -23.4% and 9.0%. Only three hybrids were found to have positive significant heterosis while 27 had significant negative heterosis; indicating reduction in MIC in hybrid combination. Similar trend was observed at India locations as well.

None of the 90 F_1 hybrids was significantly superior for UI compared to Tamcot 73. Heterosis range was -2.4% to 2.6%. Thirteen F_1 hybrids had significant positive heterosis for UI although numerically it was very low. Low range of heterosis observed for UI indicates lack of dominance for this trait. (Table 23)

No hybrid entry had significant and superior ELONG compared to Tamcot 73 (Table 23); similarly, non-significant heterosis was observed when mean performance was calculated over both locations.

None of the three testers differed in terms of mean of hybrid combinations for traits MIC and UI. Tamcot Sphinx based hybrids had better ELONG as compared to the other two testers.

Overall there was good variability present among the parental lines for the measured traits except OVCNT and ELONG at US locations. For important agronomic traits like YLD, Tamcot 73 was high yielding at WS. All Tex 7A21 had highest GINOT at India as well as at US locations. TAM13P-54 had longest UHM while TAM 06WE-621 had highest STR.

Significant heterosis was observed for all the traits except ELONG. Higher range of heterosis for YLD and PLTHT indicated plausibility of hybrid breeding program. Medium range of heterosis for OVCNT, SDCNT, GINOT, UHM, STR, and MIC inundated careful selection of parental line to improve these traits in hybrid combinations. Non-significant heterosis for ELONG and low heterosis for UI observed at US locations may be due to additive gene action which is discussed in detailed in the next section.

Table 23. Mean performance and heterobeltiosis based on best performing parent for 90 F_1 upland cotton hybrids for fiber quality traits grown at Weslaco and College Station, TX, US, 2015.

Hybrid Combination	CS		WS		Combined		Combined		Combined		Combined	
	UHM†	Hb%‡	UHM	Hb%	STR	Hb%	MIC	Hb%	UI	Hb%	ELONG	Hb%
	(mm)		(mm)		(kN m kg^{-1})		(Unit)		(Index)		(%)	
Lone Star/ Sphinx	29.8	9.3**	29.2	4.7**	301.7	-14.2**	4.3	-11.6**	85.5	-0.1	8.1	10.4
Lone Star/94L-25	31.8*	-2.7	30.6	-8.1**	306.5	-3.5	4.1	-9.6**	85.2	-0.7	8.2	28.0
Lone Star/PSC355	30.4	3.9	29.7	6.0**	297.7	-3.7	4.5	-13.3**	85.9	1.8**	8.5	13.5
Deltatype Webber/Sphinx	29.1	6.5*	29.3	5.0**	317.4	-9.8**	4.4	-9.3**	85.6	0.0	7.7	4.9
Deltatype Webber/94L-25	31.1	-4.7*	31.5	-5.6**	333.4	4.9*	4.3	-3.7	84.8	-1.1	6.7	4.6
Deltatype Webber/PSC355	30.5	4.3	29.7	6.0**	317.0	2.5	4.3	-16.9**	85.1	0.9	7.2	-4.2
Lightning Express/ Sphinx	29.5	7.9**	28.3	1.4	294.0	-16.4**	4.7	-4.0	84.5	-1.3*	7.8	6.3
Lightning Express/94L-25	29.8	-8.6**	29.8	-10.6**	294.8	-7.2**	4.4	-2.0	84.4	-1.6**	7.3	13.6
Lightning Express/PSC355	29.5	0.9	29.5	5.3**	297.2	-3.9	4.8	-6.6**	84.6	0.3	8.7	15.9
Mebane/Sphinx	29.1	6.5*	28.3	1.3	305.4	-13.2**	4.9	1.6	84.7	-1.1	7.9	8.5
Mebane/94L-25	30.5	-6.6**	29.7	-10.9**	301.7	-5.1*	4.7	4.4	84.9	-1.0	7.0	8.3
Mebane/PSC355	27.9	-4.3	28.7	2.2	293.6	-5.0*	5.1*	-1.1	84.7	0.4	8.4	12.4
Rex/Sphinx	29.2	7.0**	28.7	2.9	286.4	-18.6**	5.0	2.6	85.2	-0.5	7.4	0.8
Rex/94L-25	30.9	-5.4*	31.8	-4.7**	313.8	-1.2	4.6	3.4	84.7	-1.2*	6.8	5.5
Rex/PSC 355	29.1	-0.4	28.9	2.9	292.6	-5.3*	5.0	-3.8	84.6	0.3	8.6	15.6
Auburn 56/Sphinx	29.7	8.8**	30.2	8.4**	297.2	-15.5**	4.7	-4.0	85.5	-0.1	7.2	-1.4
Auburn 56/94L-25	33.0*	1.2	32.0	-3.9**	311.1	-2.1	4.5	0.7	85.8	0.0	7.7	19.2
Auburn 56/PSC355	29.7	1.7	29.5	5.3**	296.2	-4.2	4.6	-10.4**	84.1	-0.3	7.5	0.7
Stoneville 213/Sphinx	29.8	9.3**	30.3	8.7**	289.5	-17.7**	4.9	2.0	84.3	-1.5*	7.6	3.3
Stoneville 213/94L-25	32.1*	-1.6	31.8	-4.5**	312.1	-1.8	4.6	2.6	85.2	-0.6	6.7	3.5
Stoneville 213/PSC355	31.8*	8.7**	30.8	9.8**	323.6	4.7	4.7	-9.3**	86.1	2.0**	7.0	-7.0
DP16/ Sphinx	29.6	8.4**	30.5	9.2**	313.6	-10.8**	4.9	0.2	85.3	-0.4	7.0	-4.1
DP16/94L-25	32.6*	0.0	31.5	-5.5**	318.3	0.2	4.5	0.4	85.4	-0.4	6.9	7.1
DP16/PSC355	30.4	3.9	29.9	6.5**	308.1	-0.3	5.1*	-0.9	85.5	1.4*	8.2	10.0
Delcot 277/ Sphinx	29.7	8.8**	29.7	6.5**	313.0	-11.0**	4.7	-2.3	84.7	-1.1	8.3	12.8
Delcot 277/94L-25	33.4*	2.3	31.7	-4.8**	319.1	0.4	4.5	0.6	86.3	0.6	7.2	11.4
Delcot 277/PSC355	30.2	3.5	28.7	2.3	307.0	-0.7	5.0	-3.3	85.1	0.8	8.3	10.6
DES 422/ Sphinx	30.7	12.6**	30.8	10.4**	302.4	-14.0**	4.6	-5.9**	85.7	0.1	6.6	-9.8
DES 422/ 94L-25	32.0*	-1.9	32.1	-3.8**	319.3	0.5	4.4	-2.6	85.6	-0.2	6.8	5.8
DES 422/PSC355	32.8*	12.2**	29.8	6.3**	297.6	-3.7	3.9	-23.4**	85.3	1.1	7.5	-0.3
DP90/Sphinx	29.6	8.4**	29.7	6.6**	309.9	-11.9**	5.0	2.5	85.2	-0.5	7.0	-4.6
DP90/ 94L-25	30.4	-7.0**	32.0	-3.9**	315.2	-0.8	4.6	3.4	84.6	-1.3*	6.7	4.6
DP90/PSC355	31.0	6.1*	29.7	6.0**	334.8	8.3**	5.0	-2.5	84.9	0.6	7.1	-5.5

Table 23. Continued.

Hybrid Combination	CS		WS		Combined		Combined		Combined		Combined	
	UHM†	Hb%‡	UHM	Hb%	STR	Hb%	MIC	Hb%	UI	Hb%	ELONG	Hb%
	(mm)		(mm)		(kN m kg^{-1})		(Unit)		(Index)		(%)	
DP50/Sphinx	29.8	6.0*	29.9	7.0**	295.2	-16.1**	4.9	1.9	84.8	-0.9	7.7	5.5
DP50/ 94L-25	31.8*	-4.7*	32.1	-3.7**	308.7	-2.8	4.8	6.4**	85.6	-0.3	8.0	24.8
DP50/PSC355	30.4	6.1*	29.9	6.6**	310.1	0.3	5.1*	-0.9	85.7	1.5*	7.8	4.4
SC1/ Sphinx	29.1	5.1	28.4	1.8	309.9	-11.9**	4.8	-1.2	85.3	-0.3	7.4	1.6
SC1/ 94L-25	31.1	-3.1	31.4	-5.8**	320.3	0.8	4.6	2.3	85.2	-0.6	6.7	3.7
SC1/PSC355	30.5	3.5	29.1	3.9*	319.3	3.3	4.9	-5.2*	85.6	1.5*	7.8	4.4
PD6520/ Sphinx	29.5	6.5*	29.2	4.7**	303.2	-13.8**	5.0	2.3	85.1	-0.6	7.0	-4.1
PD6520/ 94L-25	29.8	-4.7*	29.8	-10.6**	299.5	-5.7*	4.7	4.0	84.6	-1.4*	6.7	4.9
PD6520/PSC355	29.5	-1.7	29.2	4.1*	295.4	-4.4	4.9	-4.2*	84.7	0.4	7.8	4.1
CS8606/ Sphinx	29.1	3.3	29.1	4.4*	262.0	-25.5**	4.7	-3.0	84.1	-1.7**	8.3	13.9
CS8606/ 94L-25	30.5	-4.7*	31.2	-6.3**	285.2	-10.2**	4.5	-0.4	84.2	-1.8**	7.8	21.1
CS8606/PSC355	27.9	0.4	28.7	2.2	275.2	-11.0**	4.7	-8.2**	84.5	0.1	8.3	10.8
TAM 0155/Sphinx	29.2	6.5*	29.7	6.6**	309.9	-11.9**	4.7	-3.3	84.5	-1.3*	7.4	1.1
TAM 0155/ 94L-25	30.9	-5.8**	30.4	-8.9**	296.0	-6.9**	4.2	-6.2*	83.7	-2.4**	7.2	11.4
TAM 0155/PSC355	29.1	-0.9	28.8	2.6	291.7	-5.7*	4.7	-8.3**	84.5	0.2	7.8	4.4
TAM 73840/ Sphinx	29.7	7.4**	29.6	6.0**	289.5	-17.7**	4.7	-3.3	84.6	-1.1	7.9	8.2
TAM 73840/ 94L-25	33.0*	-5.8**	30.8	-7.6**	304.8	-4.1	4.7	4.4	84.7	-1.3*	6.6	2.4
TAM 73840/PSC355	29.7	2.6	29.2	4.2*	289.3	-6.4**	4.9	-5.4*	85.1	0.9	8.3	10.8
LA 887/ Sphinx	29.8	9.3**	30.5	9.2**	317.9	-9.6**	5.0	2.1	85.6	0.0	7.4	1.4
LA 887/94L-25	32.1*	-1.9	30.7	-7.8**	327.0	2.9	4.7	3.9	85.0	-0.9	7.5	17.0
LA 887/PSC355	31.8*	3.9	29.7	5.9**	323.4	4.6	4.9	-5.0*	85.2	1.0	8.0	6.8
MD 51ne/ Sphinx	29.6	13.0**	31.0	11.0**	327.0	-7.0**	4.9	0.4	85.4	-0.3	7.3	0.0
MD 51ne/ 94L-25	32.6*	-1.2	31.4	-5.7**	344.2	8.3**	4.9	9.0**	85.2	-0.6	6.2	-3.5
MD 51ne/PSC355	30.4	3.0	29.4	4.8**	322.1	4.2	5.1*	-0.9	85.7	1.6**	7.4	-0.4
Ciano Alamos 92/ Sphinx	29.7	11.6**	29.5	5.6**	300.9	-14.4**	4.6	-4.4	84.9	-0.9	7.6	3.6
Ciano Alamos 92/ 94L-25	33.4*	-1.6	32.4	-2.9*	310.5	-2.3	4.4	-1.2	85.9	0.1	7.2	12.1
Ciano Alamos 92/PSC 355	30.2	4.8	29.4	4.8**	305.0	-1.3	4.8	-6.9*	85.2	0.9	7.5	-0.2
Ciano Cocorim 92/Sphinx	30.7	11.6**	30.0	7.5**	322.1	-8.4**	4.8	-1.3	84.7	-1.1	6.8	-7.1
Ciano Cocorim 92/94L-25	32.0*	-3.9	31.6	-5.2**	304.0	-4.3	4.6	1.9	84.5	-1.5*	6.7	3.7
Ciano Cocorim 92/PSC355	32.8*	-0.9	29.5	5.1**	307.2	-0.7	5.0	-3.2	84.6	0.3	7.5	0.4
TAM 86 GGG-30/ Sphinx	29.6	7.9**	29.5	5.7**	314.1	-10.7**	4.7	-3.1	85.9	0.4	8.6	17.1
TAM 86 GGG-30/94L-25	30.4	-6.6**	32.4	-2.9*	322.5	1.5	4.5	-0.2	85.1	-0.8	7.3	13.3
TAM 86 GGG-30/PSC355	31.0	7.0**	29.9	6.6**	324.8	5.1*	4.5	-13.6**	85.3	1.1	7.6	2.0

Table 23. Continued.

Hybrid Combination	CS		WS		Combined		Combined		Combined		Combined	
	UHM†	Hb%‡	UHM	Hb%	STR	Hb%	MIC	Hb%	UI	Hb%	ELONG	Hb%
	(mm)		(mm)		(kN m kg^{-1})		(Unit)		(Index)		(%)	
Acala Maxxa/ Sphinx	31.5	15.3**	31.0	11.0**	331.3	-5.8**	4.3	-12.4**	85.8	0.2	7.2	-2.2
Acala Maxxa/94L-25	32.0*	-1.9	32.3	-3.2*	333.4	4.9*	4.2	-7.2**	85.6	-0.2	6.5	0.8
Acala Maxxa/PSC355	30.5	4.3	30.1	7.4**	332.3	7.5**	4.5	-13.2**	85.6	1.4*	7.6	1.7
CS8601/ Sphinx	28.2	3.3	29.6	6.0**	290.5	-17.4**	4.7	-3.2	85.0	-0.7	7.8	6.3
CS8601/ 94L-25	31.5	-3.5	31.5	-5.5**	300.1	-5.6*	4.6	2.2	85.4	-0.4	7.3	13.0
CS8601/PSC355	30.2	3.5	32.4	15.6**	312.1	0.9	4.8	-7.0**	83.2	-1.4*	8.0	7.6
Acala 1517-99/ Sphinx	29.0	6.0*	29.0	4.1*	350.1	-0.4	4.6	-4.8*	85.4	-0.3	7.3	-0.3
Acala 1517-99/ 94L-25	31.6*	-3.1	31.6	-5.3**	346.4	9.0**	4.4	-3.0	87.1	1.5*	6.7	4.3
Acala 1517-99/PSC355	31.0	6.1*	29.2	4.1*	327.3	5.9*	4.9	-4.3*	86.1	2.0**	7.8	3.7
GA 161/ Sphinx	29.7	8.8**	30.6	9.6**	324.6	-7.7**	4.9	1.1	86.1	0.5	7.9	7.9
GA 161/ 94L-25	32.1*	-1.6	32.7*	-1.9	340.9	7.3**	4.5	0.9	85.7	-0.1	6.4	-0.1
GA 161/PSC355	30.5	4.3	30.3	8.0**	319.7	3.4	4.8	-6.8**	85.4	1.3*	7.8	4.1
TAM 88G-104/ Sphinx	29.3	7.4**	29.7	6.6**	309.1	-12.1**	4.7	-2.5	84.6	-1.2*	7.8	6.6
TAM 88G-104/ 94L-25	31.8*	-2.7	31.7	-4.9**	315.0	-0.9	4.5	1.0	85.5	-0.3	6.6	3.0
TAM 88G-104/PSC355	29.6	1.3	29.1	3.6*	307.9	-0.4	5.0	-3.0	85.1	0.9	8.4	11.9
Tamcot 73/ Sphinx	28.8	5.6*	29.2	4.8**	324.0	-7.9**	5.0	2.9	85.6	0.0	7.3	-0.3
Tamcot 73/94L-25	32.0*	-1.9	32.5	-2.5	318.5	0.2	4.5	1.1	85.4	-0.5	6.3	-1.6
Tamcot 73/PSC355	31.5	7.8**	31.8	13.5**	344.7	11.5**	5.0	-3.8	85.9	1.8**	7.6	1.1
All Tex 7A21/ Sphinx	29.5	7.9**	30.1	8.0**	322.3	-8.4**	5.0	3.4	85.2	-0.5	7.1	-2.5
All Tex 7A21/ 94L-25	32.3*	-1.2	32.4	-2.7	323.0	1.7	4.6	2.7	86.1	0.4	6.5	1.5
All Tex 7A21 /PSC355	29.7	1.7	29.6	5.6**	297.0	-3.9	5.0	-3.3	85.6	1.4*	9.0	20.7
UA48/ Sphinx	31.0	13.5**	31.3	12.2**	335.2	-4.7*	5.1*	4.3	85.6	0.0	7.0	-3.8
UA48/TAM 94L-25	32.6*	0.0	33.9*	1.7	346.0	8.9**	4.9	8.3**	86.4	0.7	6.5	0.5
UA48/PSC355	32.6*	11.7**	32.2	14.7**	324.4	4.9*	4.8	-7.1**	86.6	2.6**	7.7	2.5
Tamcot 73 (check)	30.0		31.4		342.8		4.68		86.3		7.2	

*Significant at P=0.05 (For mean comparison with Tamcot 73 and heterosis different than zero)
** Significant at P=0.01(For mean comparison with Tamcot 73 and heterosis different than zero)
† UHM=Fiber length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Uniformity index, ELONG=Fiber Elongation
‡ Hb% i.e. heterobeltiosis for respective trait measured.
Abbreviations- Sphinx=Tamcot Sphinx, 94L25=TAM94L-25; CS=College Station, WS=Weslaco.

Line x tester ANOVA, GCA and SCA analysis-US locations

Mean squares for the combined analysis over locations for six traits, common at College Station and Weslaco, for the line x tester ANOVA, excluding parents, were highly significant for hybrids (Table 24). Lines and testers also contributed significantly to the variation among hybrids except testers for UI. These observations again support the selection of lines and testers for this experiment since genotypes differed in the traits measured. Line x tester interaction, which suggests dominance gene action, was also significant for UHM, STR and MIC, whereas it was non-significant for GINOT, UI and ELONG.

Genotypes differed significantly for both traits OVCNT and SDCNT at CS (Table 25). Variation due to genotypes was further partitioned into parents and hybrids. Mean squares for parents and hybrids (except SDCNT for hybrids) were also significant.

At Weslaco, parents were excluded from line x tester ANOVA; however similar trends were observed for significance of source of variation for YLD and PLTHT as for traits measured at College Station (Table 26). Hybrids, lines and testers differed significantly for both YLD and PLTHT.

The results indicated preponderance of additive gene action over non-additive for all the traits since variance due to line x tester interaction was less than variance to lines or testers (Tables 24 - 26). Similar results were also observed for India locations. The results are in agreement with Wajid et al. (2011), Samreen et al. (2008), Roysdale (2003), Lingaswamy et al. (2013) and Ashokkumar et al. (2013).

Table 24. Mean squares from line x tester analysis for 90 F_1 upland cotton hybrids and parental lines for indicated traits across Weslaco and College Station, TX, US 2015.

S.O.V.	df	GINOT†	UHM	STR	MIC	UI	ELONG
Location	1	77.89	1.76	26569.69**	1.80**	4.31	4.11
Rep(Loc)	3	79.88	0.63	141.97	0.02	0.47	2.28
Hybrids	89	16.62**	6.26**	1360.87**	0.28**	2.06**	1.81**
Lines (hybrid)	29	32.04**	6.63**	3219.38**	0.52**	3.50**	1.88**
Tester(hybrid)	2	245.79**	155.04**	2494.09**	3.12**	0.57	30.96**
LXT(hybrid)	58	2.81	1.45**	355.14**	0.07**	1.15	0.77
Location X hybrids	89	1.94	0.77**	197.32	0.04	1.08	0.81
Error	256	3.29	0.48	178.74	0.03	0.85	0.62
CV (%)		5.02	2.28	4.29	4.21	1.08	10.61

*Significant at P=0.05

** Significant at P=0.01

† GINOT=Ginning out turn (%); UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UNI=Fiber uniformity index; ELONG=Fiber elongation.

Table 25. Mean squares from line x tester analysis for 90 F_1 upland cotton hybrids and parental lines for traits recorded at College Station, TX, US 2015.

S.O.V.	df	OVCNT†	SDCNT
Rep	1	16.27	1.56
Genotypes	122	10.17*	8.36*
Parents	32	11.07*	8.93*
Parent Vs Hybrids	1	13.48	110.69**
Hybrids	89	9.79*	7.01
Lines (hybrid)	29	10.30	6.18
Tester(hybrid)	2	41.35**	9.83
LXT(hybrid)	58	8.44	7.32
Error	113	6.88	5.90

*Significant at P=0.05
** Significant at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll.

Table 26. Mean squares from line x tester analysis for 90 F_1 upland cotton hybrids and parental lines for traits recorded at Weslaco, TX, US 2015.

S.O.V.	df	YLD†	PLTHT
Rep	2	11951197.60**	5851.45**
Hybrids	89	659234.90**	291.91**
Lines (hybrid)	29	905452.10*	354.12**
Tester(hybrid)	2	2394628.10**	5121.18**
LXT(hybrid)	58	473075.50*	94.27**
Error	188	332459.30	82.12

*Significant at P=0.05
** Significant at P=0.01
† YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm).

Table 27. Percent contribution of lines, testers and line x tester interaction to variation among hybrids at US locations, 2015.

SOV	OVCNT†	SDCNT	YLD	PLTHT	GINOT	UHM	STR	MIC	UI	ELONG
Lines	34.28	28.72	45.26	39.53	62.82	34.52	77.08	60.96	55.42	33.98
Testers	9.50	3.15	8.26	39.42	33.23	55.63	4.12	25.01	0.63	38.42
Line x Tester	56.22	68.13	46.48	21.05	11.02	15.17	17.01	16.33	36.68	27.56

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm); GINOT=Ginning out turn (%); UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.

The percent of the total variance among hybrids that is contributed by lines, testers and the line x tester interaction is summarized in Table 27. When the line x tester interaction contributes a greater percent of the total variance among hybrids then Singh and Chaudhary (1977) suggested that specific combinations of parents will be superior to other hybrid combinations. This situation was observed for SDCNT, BOLWT, and STR in India (Table 13) and for OVCNT, SDCNT, and YLD in the US (Table 27). Lines contributed a greater percent of the total variance than testers for GINOT, STR, MIC and UI while testers contributed the greater percent for UHM and ELONG, suggesting a greater effect for additive gene action for these traits.

Mean squares indicated that lines did not contribute significantly to hybrid performance for OVCNT and SDCNT at College Station (Table 25). This is further confirmed by GCA effects analysis that indicated that only one of the lines tested, Lone Star, significantly improved OVCNT across the three testers of this study. The average improvement contributed by Lone Star was 3.3 ovules per hybrid (OVCNT). This increase in ovules from cultivar Lone Star apparently resulted in an increase of 2.39 seeds (SDCNT) per boll in its hybrids and, although having a non-significant GCA element for OVCNT, but second highest numerically, DP50 also had positive and significant GCA for SDCNT. These data suggest that hybrids with Lone Star or DP50 as one of the parents tended to retain more seeds per boll in the hybrid combinations. Lone Star also exhibited a positive and significant GCA in India (Table 14).

Correlation analysis among SDCNT, OVCNT, YLD and BOLWT from India locations (data not presented) revealed that SDCNT and OVCNT were significantly correlated (r =0.37 at AWB and r=0.41 at HYD) as expected, however they were poorly correlated with YLD. Both OVCNT (r=0.22 at AWB and 0.30 at HYD) and SDCNT (r=0.20 at AWB and r=0.35 at HYD) were significantly correlated to BOLWT, which in turn was correlated to YLD (r=0.41 at AWB and r=0.27 at HYD). This means that genotypes like Lone Star and DP50 can be used for increased SDCNT that may contribute to YLD through increased boll weight.

GCA effects for YLD at Weslaco were significant for seven lines; three lines had positive and four were negative for GCA effects. DP50, LA 887 and Tamcot 73 combined with the three testers for significant and positive GCA effects for YLD (Table 28). Tamcot 73 also had significant GCA for YLD at the India locations (Table 14) indicating usefulness and stability of this genotype in both countries.

Table 28. GCA effects of lines from line x tester analysis in upland cotton across Weslaco and College Station, TX, US, 2015.

Genotype	OVCNT† (No.)	SDCNT (No.)	PLTHT (cm)	YLD (kg ha^{-1})	GINOT (%)	UHM (mm)	STR (kN m kg^{-1})	MIC (Unit)	UNI (Index)	ELONG (%)
Lone Star	3.32**	2.39*	12.39**	-765.15**	-1.72**	-0.34	-10.02**	-0.42**	0.38	0.82**
Deltatype Webber	0.70	0.41	9.47**	-97.56	-3.03**	-0.21	10.93**	-0.37**	-0.02	-0.25
Lightning Express	0.65	1.14	6.10*	66.94	-2.31**	-1.04**	-16.33**	-0.08	-0.67**	0.47*
Mebane	1.60	0.51	1.00	-401.83*	-0.29	-1.39**	-11.43**	0.20**	-0.44	0.33
Rex	0.65	0.01	-0.47	-208.28	-0.96*	-0.65**	-14.04**	0.16**	-0.34	0.16
Auburn 56	-1.24	-0.74	2.80	226.18	-2.08**	0.28	-10.19**	-0.10*	-0.07	0.03
Stoneville 213	-0.46	0.71	1.19	-325.84	0.50	0.59**	-7.72*	0.07	-0.24	-0.32
DP16	1.59	1.74	-0.16	182.69	0.23	0.32	1.71	0.12*	0.23	-0.07
Delcot 277	-1.10	-0.93	3.91	-72.27	-0.98**	0.08	1.39	0.04	0.18	0.45*
DES 422	0.08	-0.02	-7.32*	-117.85	-0.01	0.99**	-2.98	NA	NA	NA
DP90	-1.83	-1.14	9.27**	161.86	0.64	0.01	8.32*	-0.32**	0.41	-0.62**
DP50	2.05	2.11*	-0.57	451.10*	0.09	0.11	-6.98*	0.17**	-0.28	-0.52*
SC1	-0.83	-0.81	-3.80	-289.01	0.50	-0.53**	4.85	0.24**	0.16	0.41*
PD6520	-0.16	-0.13	-3.85	33.24	0.09	-0.88**	-11.98**	0.05	0.22	-0.14
CS8606	-0.60	-0.13	-3.52	-11.12	1.15*	-0.77**	-37.51**	0.15**	-0.39	-0.30

Table 28. Continued.

Genotype	OVCNT† (No.)	SDCNT (No.)	PLTHT (cm)	YLD (kg ha^{-1})	GINOT (%)	UHM (mm)	STR (kN m kg^{-1})	MIC (Unit)	UI (Index)	ELONG (%)
TAM 0155	1.82	0.33	-11.95**	-291.37	0.56	-0.78**	-12.47**	-0.07	-0.92**	0.69**
TAM 73840	-0.18	-0.61	-15.44**	-216.88	1.20**	-0.48**	-17.12**	-0.16**	-0.94**	0.01
LA 887	0.90	0.61	8.61**	494.44*	2.38**	0.08	11.13**	0.05	-0.37	0.15
MD 51ne	-1.98	-0.88	0.72	184.63	1.47**	0.38*	19.43**	0.13**	0.08	0.20
Ciano Alamos 92	1.42	0.68	-3.83	-263.52	1.31**	0.27	-6.20	0.25**	0.24	-0.45*
Ciano Cocorim 92	0.50	0.04	-1.52	133.91	0.52	-0.09	-0.57	-0.08	0.12	-0.03
TAM 86 GGG-30	-0.78	-1.53	-2.49	-393.04*	-2.08**	0.17	9.25**	0.08	-0.59*	-0.45*
Acala Maxxa	-0.60	-0.08	-8.19**	-414.35*	-1.09*	0.75**	20.59**	-0.17	0.22	0.33
CS8601	1.32	1.39	-5.13	-11.07	-1.12*	0.28	-10.77**	-0.40**	0.47*	-0.32
Acala 1517-99	-1.10	-2.16*	6.53*	76.45	-0.63	-0.28	30.61**	-0.01	-0.65**	0.25
GA 161	-1.21	-0.48	4.90	134.49	0.90*	0.62**	16.75**	-0.09	0.99**	-0.23
TAM 88G-104	-1.11	-0.63	3.72	367.31	-0.49	-0.23	-0.97	0.04	0.53*	-0.07
Tamcot 73	0.16	-0.10	-3.02	805.78**	0.71	0.59**	16.32**	0.05	-0.11	0.15
All Tex 7A21	-1.85	-0.74	1.05	230.21	3.92**	0.23	2.43	0.12*	0.39	-0.42*
UA48	-1.55	-0.86	-2.33	79.72	0.61	1.92**	23.55**	0.17**	0.44	0.12
SE (Lines)	1.07	0.99	3.02	192.19	0.45	0.18	3.46	0.05	0.23	0.20

*Significantly different than zero at P=0.05
** Significantly different than zero at P=0.01
† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm); GINOT=Ginning out turn (%); UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.
*** OVCNT and SDCNT: - Data from College Station only. YLD and PLTHT: - Data from Weslaco only.

GCA effects for PLTHT (Weslaco location only) indicated that DES 422 (-7.32 cm), TAM 0155 (-11.95 cm), TAM 73840 (-15.44 cm) and Acala Maxxa (-8.19 cm) combined with the testers in this study for reduced PLTHT (Table 28). TAM 0155 and TAM 73840 also showed significant and negative, thus reduced PLTHT, GCA in India. These lines were included in this study because they were developed by the Texas A&M AgriLife Research cotton breeding program at College Station for mechanical harvest during the era when the US was moving toward 100% mechanical harvest (Smith and Niles, 1990). Such genotypes found in the US National Plant Germplasm System could be of value in developing such hybrid phenotypes adapted to India.

All Tex 7A21 cultivar was the best general combiner for GINOT across the two locations in the US (Table 28). This line added an average of 3.92 % lint compared with the average of all lines combined with the three testers. It was also the best general combiner in India (Table 14). Other positive and significant general combiners in the US were CS8606 (1.15%), TAM 73840 (1.20%), LA 887 (2.38%), MD 51ne (1.47%), Ciano Almos 92 (1.31%), and GA 161 (0.90%).

Eight lines had negative and significant UHM GCA while seven had positive and significant values (Table 28). Lines that exhibited positive and significant length GCA in both the US and India locations were MD 51ne, Acala Maxxa, GA 161, Tamcot 73 and UA48 (Table 14 and Table 28). Tamcot 73 and UA48 also combined positively with the testers used in this study to produce hybrids with improved YLD, UHM, STR, and MIC in both the US and India. Along with eight other lines, Tamcot 73 and UA48 exhibited positive and significant GCA for STR with UA48 adding an average of 23.6 kN m kg^{-1}

to the three testers and Tamcot 73 adding 16.3 kN m kg^{-1}. Acala 1517-99 had highest GCA for STR (30.6 6 kN m kg^{-1}) along with several other lines. The combining ability for STR was expected for MD 51ne, Acala Maxxa, and Acala 1517-99. It should be noted that these three are from breeding programs that have invested many years in the development of genotypes with improved strength and that Acala 1517-99 appears in the pedigrees of many current US cultivars (Bowman et al., 2006). However, the performance of Deltatype Webber is interesting because it was released in 1922, an era when no objective measurement of STR existed. Schwartz and Smith (2008) reported that it has STR equivalent to modern US cultivars and was superior in STR to all tested cultivars from 1906 to about 2000.

Performance of these lines in this line x tester study suggests that they are of value to plant breeders in developing pure line cultivars or hybrids with excellent fiber quality.

Ten, three and five lines had significant superior GCA for MIC, UI and ELONG respectively. UA48 exhibited significant GCA for MIC, which is probably a positive attribute for India since the MIC values recorded for the LxT hybrids in India were below the 3.5 to 4.9 desirable range (Table 11) but not in the US (Table 28).

GCA effects for the three testers differed for all the traits except SDCNT, STR and UI (Table 29). Tamcot Sphinx had significant positive GCA for OVCNT (0.95) and YLD (178 kg ha^{-1}), although it combined with the 30 lines to reduce UHM (-0.72 mm). TAM94L-25 was only tester which had positive and significant GCA for UHM (1.20 mm) but it was a poor and undesirable combiner for YLD, PLTHT, GINOT, and

ELONG. Its lower GCA for MIC could be a positive attribute for the US but a negative attribute for India while its negative GCA for PLTHT could be a positive for Indian hybrid production. However significant negative GCA for YLD (-132. kg ha^{-1}), GINOT (-1.51%), and ELONG (-0.51) suggests careful selection of complementing parent in hybrid combination to avoid tradeoff for these traits. PSC355 was a poor combiner when evaluated in both India and US. It had negative GCA for GINOT, UHM, and ELONG. Its significant and positive GCA for PLTHT is undesirable for India but its positive GCA for MIC could suggest a valuable parent for developing hybrids. Overall, PSC355 would be a poor parent for hybrid production in India based on its performance for GCA with the lines used in this study.

All hybrid combinations based on Tamcot Sphinx and TAM94L-25 exhibited non-significant SCA for OVCNT, while only Deltatype Webber/PSC355 (3.68) was significant (Table 30). Similarly, no entry had positive significant SCA for SDCNT while Mebane/Tamcot Sphinx (-3.54) was significant for negative SCA. (Table 30)

Two hybrid combinations, i.e., PD6520/Tamcot Sphinx (854 kg ha^{-1}) and Tamcot 73/PSC355 (1078 kg ha^{-1}) exhibited positive significant SCA effect for YLD (Table 30). It is interesting to note that PD6520/PSC355 and Tamcot 73/Tamcot Sphinx had negative SCA effect indicating importance of parental selection for hybrid combinations to achieve better heterosis.

Table 29. GCA effects of testers from line x tester analysis in upland cotton across Weslaco and College station, TX, US, 2015.

Genotype	OVCNT†	SDCNT	YLD	PLTHT	GINOT	UHM	STR	MIC	UI	ELONG
Tamcot Sphinx	0.95**	0.46	178.35**	-0.17	0.53	-0.72**	-2.66	0.06	-0.05	0.05
TAM 94L-25	-0.43	-0.18	-132.21*	-7.49**	-1.51**	1.20**	4.76	-0.17**	0.08	-0.51*
PSC355	-0.57	-0.30	-56.03	8.02**	0.98*	-0.48**	-2.10	0.11*	-0.04	0.46*
SE (tester)	0.33	0.31	60.77	0.95	0.45	0.18	3.46	0.05	0.23	0.02

*Significantly different than zero at P=0.05

** Significantly different than zero at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm); GINOT=Ginning out turn (%); UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.

***OVCNT and SDCNT: - Data from College Station only. YLD and PLTHT: - Data from Weslaco only.

For PLTHT, only TAM 0155 and TAM94L-25 combined specifically for reduced PLTHT at -12.52 cm (Table 30). Surprisingly, tester Tamcot Sphinx combined specifically with Acala Maxxa for increased PLTHT.

For GINOT, two F_1 hybrids based on Tamcot Sphinx involving Stoneville 213 (1.53%) and DP90 (1.42%) as female parents had positive and significant SCA effects. Tamcot Sphinx also combined with these lines in this study for a positive and significant GCA for YLD, indicating usefulness of this line for YLD and higher GINOT in hybrid combinations.

Thirteen genotypes for UHM and 16 for STR had significant and positive SCA estimates (Table 30). CS8601/PSC355 had the highest SCA effect for UHM (1.35 mm), while Rex/PSC355 (18.31 kN m kg^{-1}) had highest SCA effect for STR. Six, four and five hybrid combinations exhibited significant SCA for MIC, UI and ELONG respectively. Acala 1517-99/PSC355 (0.20), Stoneville 213/PSC 355 (1.14) and All Tex 7A21/PSC355 (1.00) had highest SCA effect for MIC, UI and ELONG respectively.

Although PSC355 was a poor general combiner with the 30 lines used in this study in the US for UHM and PLTHT, it was a good general combiner for GINOT, ELONG, and MIC (in India), and it apparently carries some dominant alleles that result in specific combinations that result in desirable phenotypes (Tables 29 and 30). This tester appears to have contributing complementing alleles for fiber qualities in hybrid combinations with these lines since among 30 F_1 hybrids, five SCA effects were significant and positive for UHM and 11 for STR.

Table 30. SCA effects from line x tester analysis for 90 upland cotton F_1 hybrids across US locations 2015.

Line/Tester	OVCNT†			SDCNT			YLD			PLTHT			GINOT		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Lone Star	2.39	-0.61	-1.78	1.31	-1.44	0.13	-62.51	152.18	-87.73	-9.49	0.68	8.81	-0.26	0.08	-0.11
Deltatype Webber	-2.39	-1.29	3.68*	-1.09	-0.34	1.43	418.23	-430.94	14.66	-2.25	-2.58	4.82	-0.49	0.39	0.10
Lightning Express	2.21	-1.09	-1.12	-0.28	0.28	0.00	509.57	-140.44	-367.19	-1.24	-0.57	1.80	-0.53	0.25	0.28
Mebane	-0.69	0.06	0.63	-3.54*	0.76	2.78	304.68	-172.43	-130.31	1.13	7.53	-8.67	-0.08	-0.24	0.32
Rex	0.01	2.26	-2.27	-1.14	2.61	-1.47	-48.20	-160.18	210.32	-1.34	-1.00	2.34	-0.44	0.34	0.10
Auburn 56	1.57	-1.14	-0.42	2.87	-3.30	0.43	-142.97	537.52	-392.60	4.77	2.83	-7.60	-0.61	0.08	0.54
Stoneville 213	-2.88	1.38	1.50	-1.59	1.56	0.03	9.19	174.93	-182.17	-0.64	4.73	-4.10	1.53*	-1.01	-1.09
DP16	0.67	0.58	-1.25	2.47	0.48	-2.95	-536.82	388.54	150.22	2.25	-1.41	-0.84	0.08	-0.55	0.47
Delcot 277	-2.09	2.11	-0.02	0.24	1.94	-2.18	-27.55	-44.33	73.82	1.75	3.39	-5.14	0.59	0.26	-0.85
DES 422	1.42	-2.72	1.30	-0.39	-0.24	0.63	-98.17	41.72	NA	-0.76	-3.32	4.08	0.91	-0.31	-0.05
DP90	-0.31	-1.66	1.97	-1.29	-1.49	2.78	-51.98	281.27	-227.34	-2.05	5.02	-2.98	1.42*	-0.01	-1.41*
DP50	0.26	1.01	-1.27	-0.29	0.56	-0.27	387.87	-226.90	-159.02	4.70	-3.23	-1.47	-0.12	-0.01	0.13
SC1	-2.96	0.69	2.27	-2.33	0.28	2.05	229.72	-280.79	53.02	1.57	-1.70	0.14	0.28	-0.15	-0.13
PD6520	2.47	-1.77	-0.70	1.59	-0.86	-0.73	854.62*	-199.19	-653.48*	0.13	1.13	-1.25	-0.20	0.21	0.22
CS8606	1.46	-2.09	0.63	1.29	-1.66	0.37	-190.03	357.43	-165.45	4.61	1.38	-5.99	-0.46	0.29	0.17
TAM 0155	1.59	-0.16	-1.43	-0.11	0.69	-0.58	387.48	-682.13*	296.59	8.04	-12.52*	4.48	-1.14	0.42	0.72
TAM 73840	0.24	2.99	-3.23	-0.08	3.28	-3.20	-319.91	385.08	-63.23	-4.80	3.53	1.27	-0.42	-0.38	0.80
LA 887	-0.04	-1.89	1.93	0.86	-1.89	1.03	-199.53	73.46	128.01	-5.71	7.12	-1.41	-0.47	0.08	0.38
MD 51ne	-1.96	0.79	1.17	-1.36	-0.41	1.77	-96.75	-23.86	122.56	6.61	-9.09	2.48	-1.11	0.08	1.03
Ciano Alamos 92	0.19	1.54	-1.73	-1.36	1.59	-0.23	-347.54	-250.72	600.20	-1.71	-1.21	2.92	-0.46	0.08	0.39
Ciano Cocorim 92	0.86	-0.39	-0.47	-0.73	0.63	0.10	-244.37	142.58	103.74	-1.62	-0.76	2.38	0.02	0.99	-1.01
TAM 86 GGG-30	-0.71	-2.81	3.52	-0.86	-1.41	2.27	-352.62	83.17	271.39	-1.00	-0.15	1.15	-0.49	1.11	-0.61
Acala Maxxa	2.09	-0.26	-1.83	2.01	-1.14	-0.87	357.39	40.72	-396.17	10.42*	-3.14	-7.28	0.13	0.36	-0.72
CS8601	1.19	2.34	-3.53	2.57	-0.02	-2.55	48.32	-244.03	197.66	-3.45	9.66	-6.21	-0.44	-0.37	0.80
Acala 1517-99	-1.63	-0.07	1.70	1.22	-1.72	0.50	186.56	158.05	-342.67	-0.57	2.57	-2.00	0.30	0.45	-0.70
GA 161	0.97	-2.07	1.10	1.34	-1.51	0.17	173.68	342.01	-513.74	0.30	-5.83	5.54	-0.20	-0.48	0.68
TAM 88G-104	-2.23	2.28	-0.05	-0.66	2.29	-1.63	-355.68	298.05	59.58	-3.92	-1.42	5.35	0.19	-0.64	0.44
Tamcot 73	-0.11	1.04	-0.93	-1.51	-0.11	1.62	-804.07*	-272.22	1078.24*	-5.99	6.91	-0.92	0.83	0.26	-1.12
All Tex 7A21	-1.94	0.76	1.18	-1.19	0.16	1.03	354.93	-146.08	-206.90	1.84	-1.96	0.11	1.14	-1.43*	0.29
UA48	0.36	0.16	-0.52	2.02	0.43	-2.45	-308.21	-147.15	457.30	-1.58	-6.61	8.19	0.49	-0.24	-0.25
SE (SCA effects)	1.85	1.85	1.85	1.71	1.71	1.71	332.89	332.89	332.89	5.23	5.23	5.23	0.58	0.58	0.58

*Significantly different than zero at P=0.05

** Significantly different than zero at P=0.01

† OVCNT=Number of ovules per boll; SDCNT=Number of seeds per boll; YLD=Seed cotton yield kg ha^{-1}; PLTHT=Plant height (cm); GINOT=Ginning out turn (%)

***OVCNT and SDCNT: - Data from CS only. YLD and PLTHT: - Data from WS only. Abbreviations- T1=Tamcot Sphinx, T2=TAM94L-25, T3=PSC355

Table 30. Continued.

Line/Tester	UHM†			STR			MIC			UI			ELONG		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Lone Star	0.12	-0.34	0.39	2.69	0.08	6.93	-0.06	-0.06	0.07	0.00	-0.47	0.39	-0.24	0.47	-0.24
Deltatype Webber	-0.27	-0.05	0.31	-2.57	6.10	12.95**	0.01	0.16*	-0.17*	0.48	-0.45	-0.03	0.44	0.04	-0.48
Lightning Express	0.11	-0.74**	0.63**	1.35	-5.28	1.57	-0.02	-0.05	0.07	0.05	-0.22	0.16	-0.19	-0.10	0.29
Mebane	0.31	-0.18	-0.13	7.83	-3.32	3.53	-0.03	-0.04	0.08	-0.04	0.05	-0.01	0.12	-0.30	0.18
Rex	-0.13	0.45	-0.31	-8.58	11.46*	18.31**	0.06	-0.04	-0.02	0.37	-0.18	-0.18	-0.27	-0.31	0.58*
Auburn 56	0.05	0.53*	-0.58*	-1.65	4.85	11.71**	0.00	0.10	-0.10	0.43	0.56	-1.00**	-0.30	0.70**	-0.40
Stoneville 213	-0.15	-0.24	0.74**	-11.76**	3.42	10.28*	0.12	0.01	-0.22**	-0.62*	0.20	1.14**	0.39	0.04	-0.62*
DP16	0.12	0.04	-0.16	2.92	0.21	7.07	-0.02	-0.14*	0.17*	-0.07	-0.08	0.14	-0.41	0.02	0.39
Delcot 277	-0.05	0.73**	-0.69**	2.66	1.32	8.18	-0.06	-0.06	0.12	-0.61*	0.88**	-0.26	0.31	-0.22	-0.09
DES 422	0.11	-0.53*	0.33	-3.57	5.88	12.74**	0.12	0.16*	-0.55**	0.11	-0.03	-0.26	-0.28	0.48	0.17
DP90	-0.03	-0.27	0.30	-7.41	-9.53*	-2.68	0.04	-0.06	0.03	0.35	-0.34	0.00	0.01	0.31	-0.32
DP50	-0.28	-0.01	0.30	-6.82	-0.70	6.15	-0.06	0.01	0.05	-0.48	0.13	0.35	-0.18	0.68*	-0.50
SC1	-0.61*	0.43	0.18	-3.94	-0.97	5.89	-0.02	0.01	0.01	-0.01	-0.24	0.26	0.09	-0.13	0.04
PD6520	0.36	-0.39	-0.08	6.22	-4.93	1.93	0.05	-0.01	-0.03	0.33	-0.27	-0.08	-0.17	0.11	0.18
CS8606	-0.17	0.36	-0.20	-9.43*	6.29	13.15**	0.01	0.01	-0.02	-0.08	-0.15	0.23	0.15	0.16	-0.31
TAM 0155	0.56*	-0.28	-0.28	13.38**	-7.96	-1.11	0.09	-0.16*	0.07	0.30	-0.59	0.29	-0.11	0.22	-0.11
TAM 73840	0.26	-0.33	0.08	-2.37	5.51	12.36**	-0.12	0.11	0.01	-0.15	-0.20	0.34	0.27	-0.50	0.23
LA 887	0.46*	-0.43	-0.03	-2.18	-0.57	6.28	0.06	0.00	-0.06	0.36	-0.37	0.01	-0.27	0.39	-0.12
MD 51ne	0.87*	-0.23	-0.64**	-1.46	8.38	15.24**	-0.15*	0.11	0.04	-0.02	-0.27	0.29	0.28	-0.28	0.00
Ciano Alamos 92	-0.08	0.39	-0.31	-1.92	0.28	7.13	-0.04	-0.01	0.06	-0.40	0.51	-0.11	0.11	0.30	-0.41
Ciano Cocorim 92	0.58*	-0.01	-0.57*	13.64**	-11.82**	-4.96	-0.05	-0.04	0.09	0.15	-0.18	0.02	-0.24	0.18	0.06
TAM 86 GGG-30	-0.39	-0.17	0.34	-4.17	-3.20	3.65	0.11	0.12	-0.20**	0.56	-0.41	-0.05	0.75**	0.02	-0.61*
Acala Maxxa	0.76**	-0.15	-0.39	1.69	-3.57	3.29	-0.11	0.03	0.05	0.16	-0.13	-0.03	-0.02	-0.14	0.02
CS8601	-0.96**	-0.38	1.35**	-7.73	-5.54	1.31	-0.06	0.07	-0.01	0.53	0.78*	-1.32**	0.03	0.08	-0.11
Acala 1517-99	-0.40	0.28	0.02	10.51*	-0.64	6.22	-0.05	-0.09	0.20**	-0.77*	0.84**	-0.09	0.03	0.00	0.08
GA 161	-0.08	0.24	-0.16	-1.13	7.73	14.58**	0.10	-0.04	-0.06	0.39	-0.14	-0.26	0.48	-0.44	-0.04
TAM 88G-104	0.11	0.33	-0.43	1.09	-0.44	6.41	-0.08	-0.05	0.13*	-0.45	0.38	0.06	0.15	-0.46	0.31
Tamcot 73	-1.22**	0.12	1.24**	-1.29	-14.20**	-7.35	0.12	-0.11	0.02	0.03	-0.30	0.33	0.22	-0.19	0.07
All Tex 7A21	-0.05	0.53*	-0.48*	10.83*	4.20	11.05*	0.09	-0.09	0.00	-0.37	0.40	-0.02	-0.47	-0.53*	1.00**
UA48	-0.42	-0.10	0.52*	2.66	6.03	12.88**	0.10	0.13*	-0.23**	-0.55	0.14	0.42	-0.07	-0.08	0.15
SE (SCA effects)	0.23	0.23	0.23	4.46	4.46	4.46	0.06	0.06	0.06	0.30	0.30	0.30	0.26	0.26	0.26

*Significantly different than zero at P=0.05
** Significantly different than zero at P=0.01
† UHM=Upper half mean length in mm; STR=Fiber strength in kN m kg^{-1}; MIC=Micronaire; UI=Fiber uniformity index; ELONG=Fiber elongation.
Abbreviations- T1=Tamcot Sphinx, T2=TAM94L-25, T3=PSC355

CHAPTER IV

CONCLUSIONS

Heterosis and combining ability studies reported herein using diverse US cultivars with comparative performance in US and India has demonstrated heterosis and combining ability for important traits such as yield and fiber qualities. As Indian cotton breeding progresses towards synchronous maturity and compact upland cotton phenotypes suitable for high density conditions, the following conclusions may help to identify suitable US germplasm to be used by Indian breeders.

1) Performance of select US genotypes such as Tamcot 73, TAM 94L-25 and UA48 in India was comparable for yield and superior for fiber qualities relative to locally adapted cultivars. Data on combining ability revealed a number of good combiners for the traits measured whereas the line x tester ANOVA indicated predominance of additive gene action over non-additive. This indicates that after initial screening, US germplasm can be used for the improvement of existing Indian cotton germplasm for yield, fiber quality, and value-added traits like GINOT and reduced plant height for high density planting.

2) Significant heterosis was observed for YLD and yield contributing traits like BOLWT, SDINX, PLTHT and GINOT. Among fiber quality traits, comparatively better heterosis was observed for SL, STR and MIC while heterosis range was low for UI and ELONG. With the representative US genotypes used in this study, it can be stated that heterosis is plausible even under high density planting conditions.

3) Hybrids can be bred for high density planting conditions as indicated by 83% heterosis for YLD over the tester parent observed in India and 72% at the US locations. However, this demands careful parental selection based on GCA estimates and negative heterosis observed in this study. At WS, the highest yield of 6377 kg ha^{-1} for hybrid Tamcot 73/PSC355 was recorded while the highest yield among the cultivar checks was 5161 kg ha^{-1} for Tamcot 73; however, all the cultivar checks were significantly lower than highest yielding hybrid. This underlines the importance of hybrids provided efficient seed production methods are available.

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